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(54) **HEAD-WORN AUGMENTED REALITY DISPLAY**

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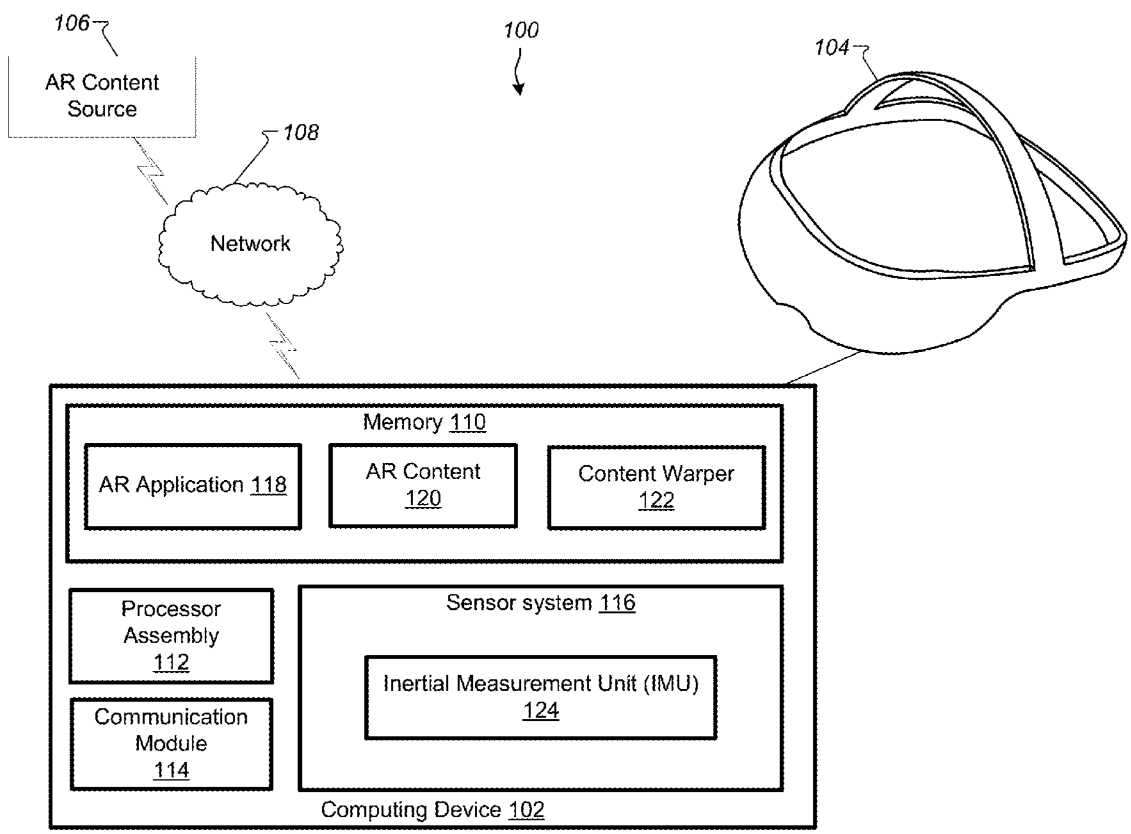
(57) **ABSTRACT**

Systems, devices, and apparatuses for a head-worn augmented reality display are provided. An example head-mounted display device includes a frame, a combiner, and a microdisplay device. The frame may have a structure that is configured to be worn by a user. The combiner may be attached to the frame and may include a curved transparent structure having a reflective surface. The microdisplay device may be attached to the frame and configured to, when the frame is worn by the user, emit image content that crosses in front of the user's face and intersects with the reflective surface of the combiner. Example combiners may have a positive wrap angle.



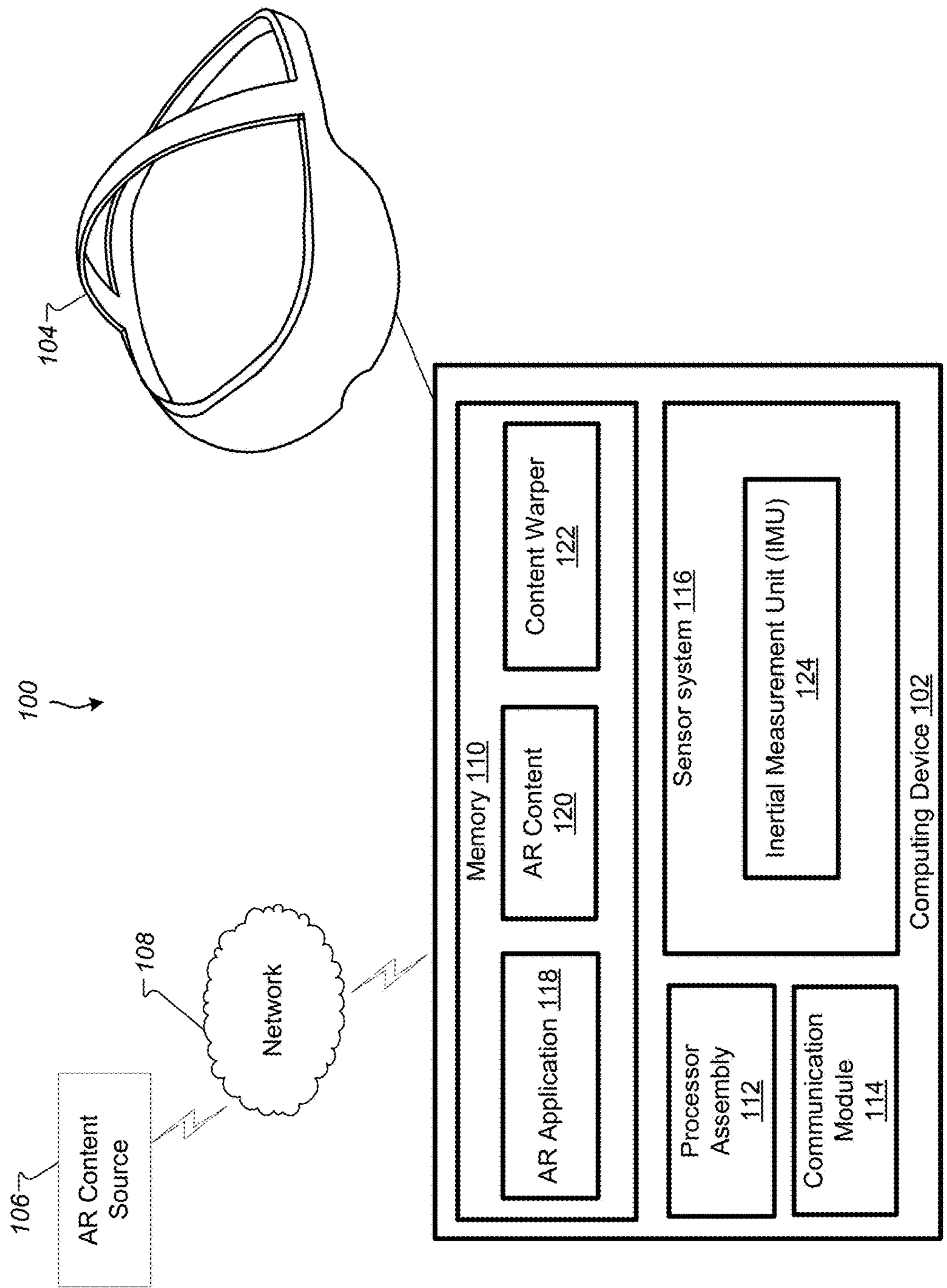

100
104
106
AR Content Source
108
Network
Memory 110
AR Application 118
AR Content 120
Content Warper 122
Sensor system 116
Inertial Measurement Unit (IMU) 124
Processor Assembly 112
Communication Module 114
Computing Device 102

FIG. 1

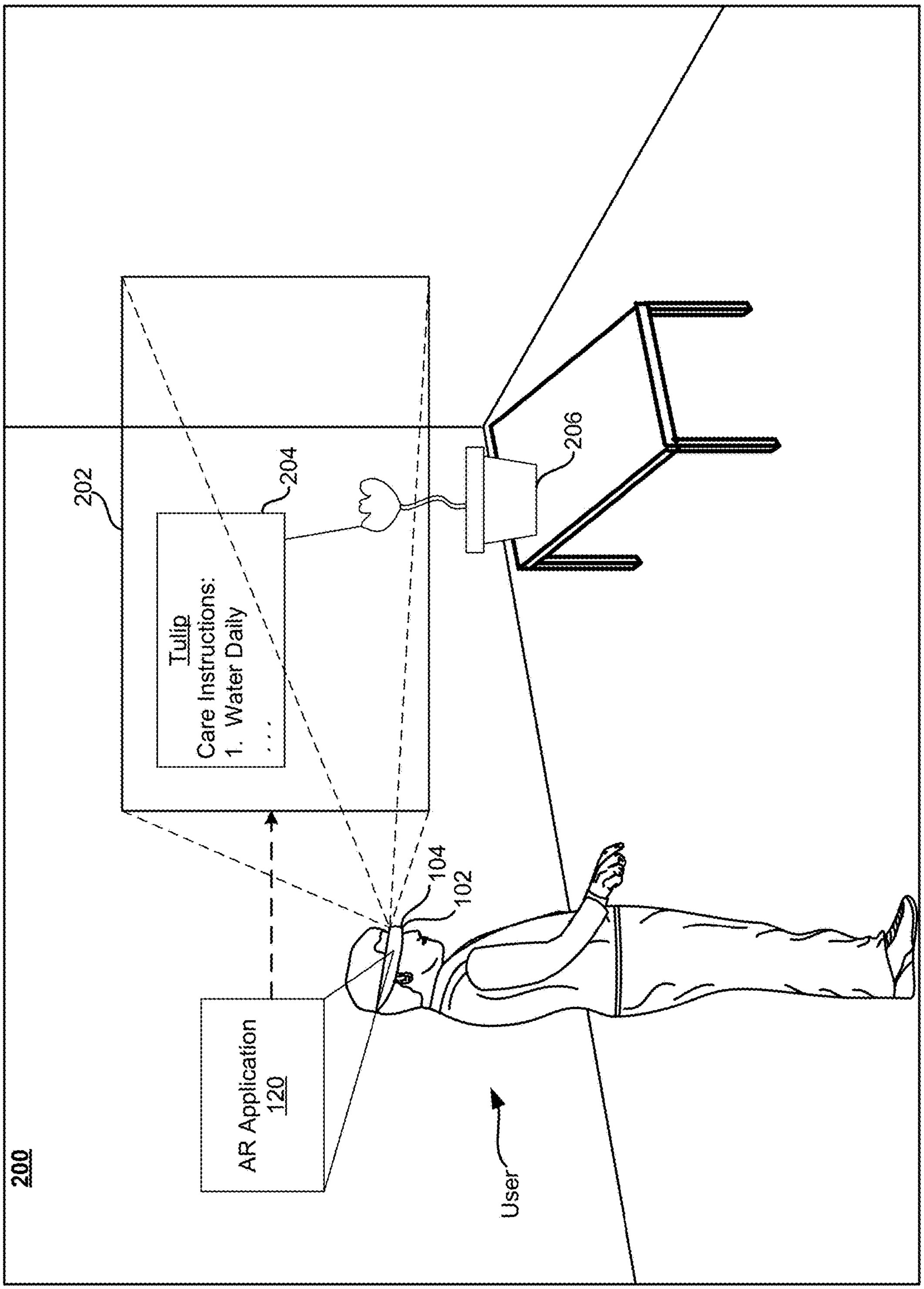

200
AR Application
120
User
202
204
206
104
102
Tulip
Care Instructions:
1. Water Daily
. . .

FIG. 2

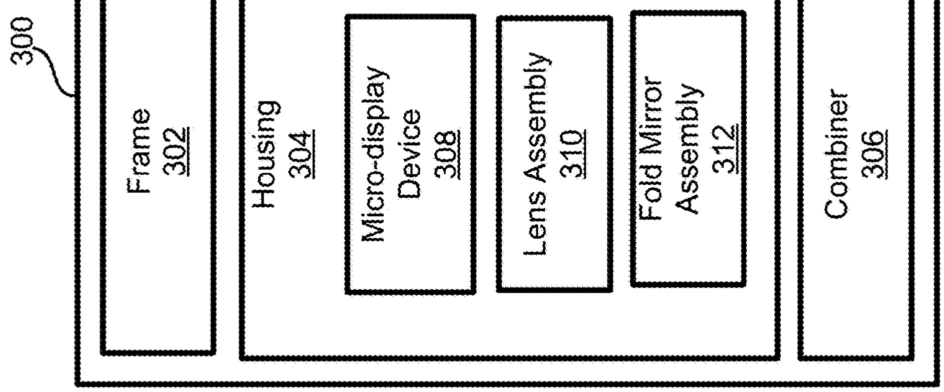

300
Frame
302
Housing
304
Micro-display
Device
308
Lens Assembly
310
Fold Mirror
Assembly
312
Combiner
306

FIG. 3

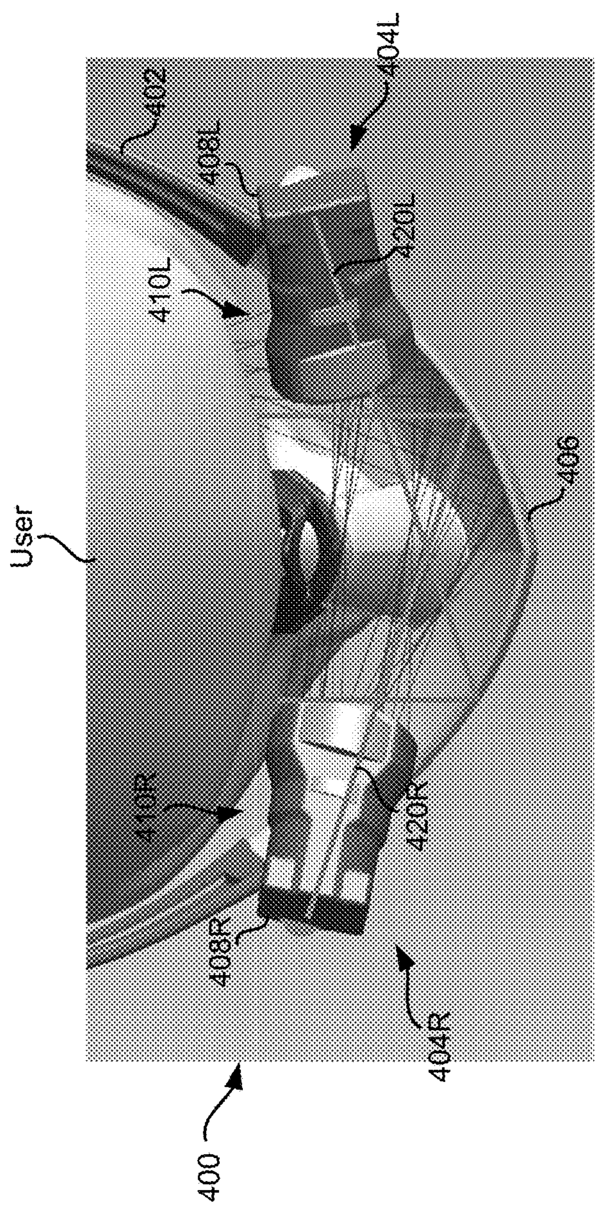
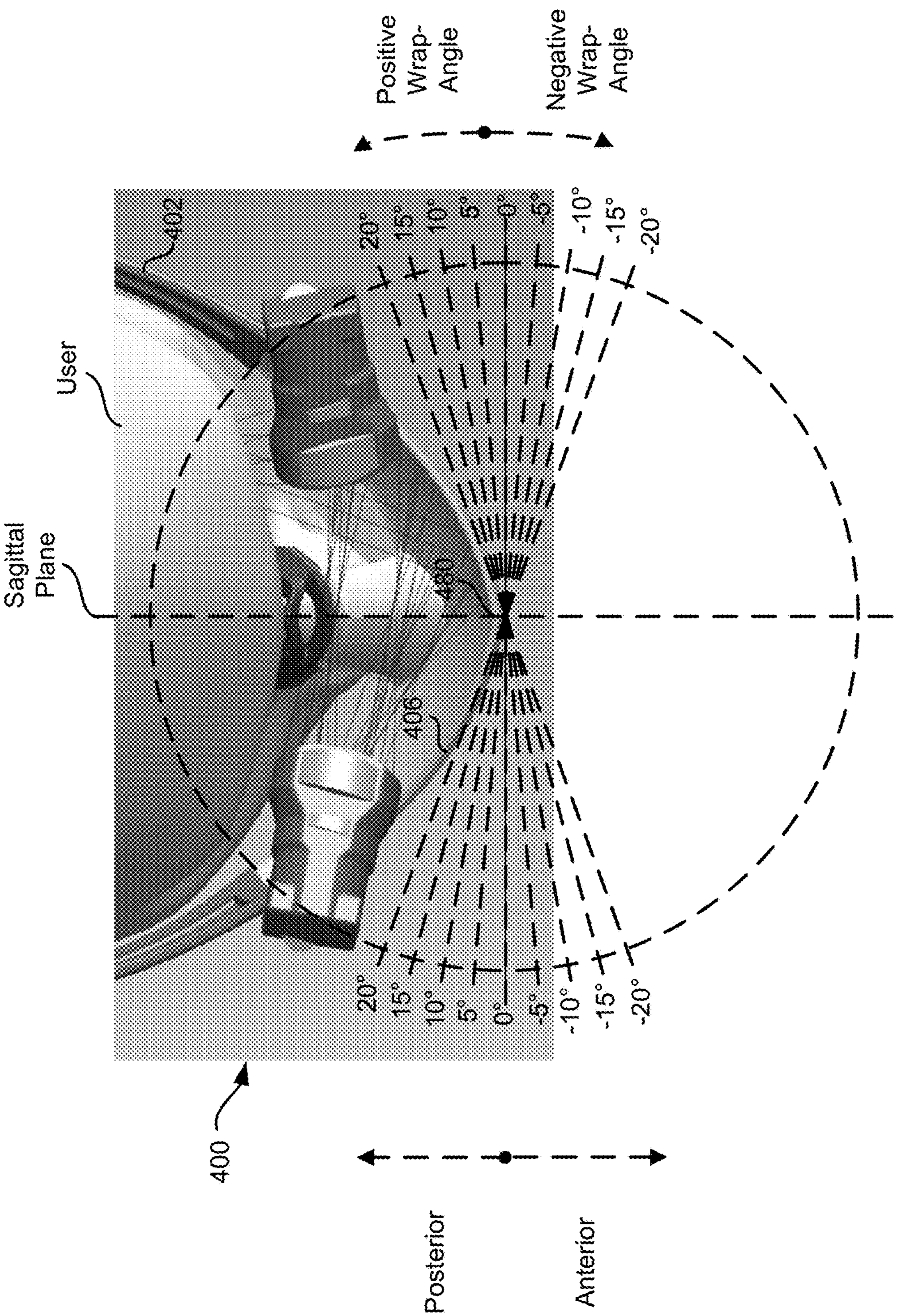


FIG. 4A



Positive Wrap-Angle
Negative Wrap-Angle
User
Sagital Plane
402
480
406
400
20°
15°
10°
5°
0°
-5°
-10°
-15°
-20°
Posterior
Anterior

FIG. 4B

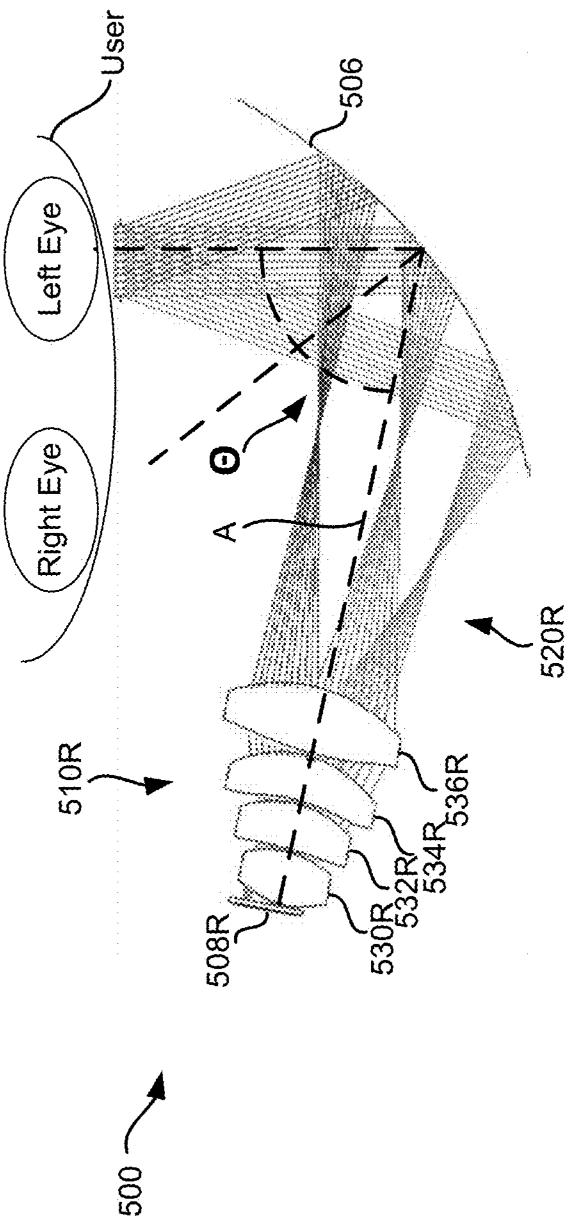

User
506
Left Eye
Right Eye
Θ
A
520R
510R
536R
534R
532R
530R
508R
500

FIG. 5

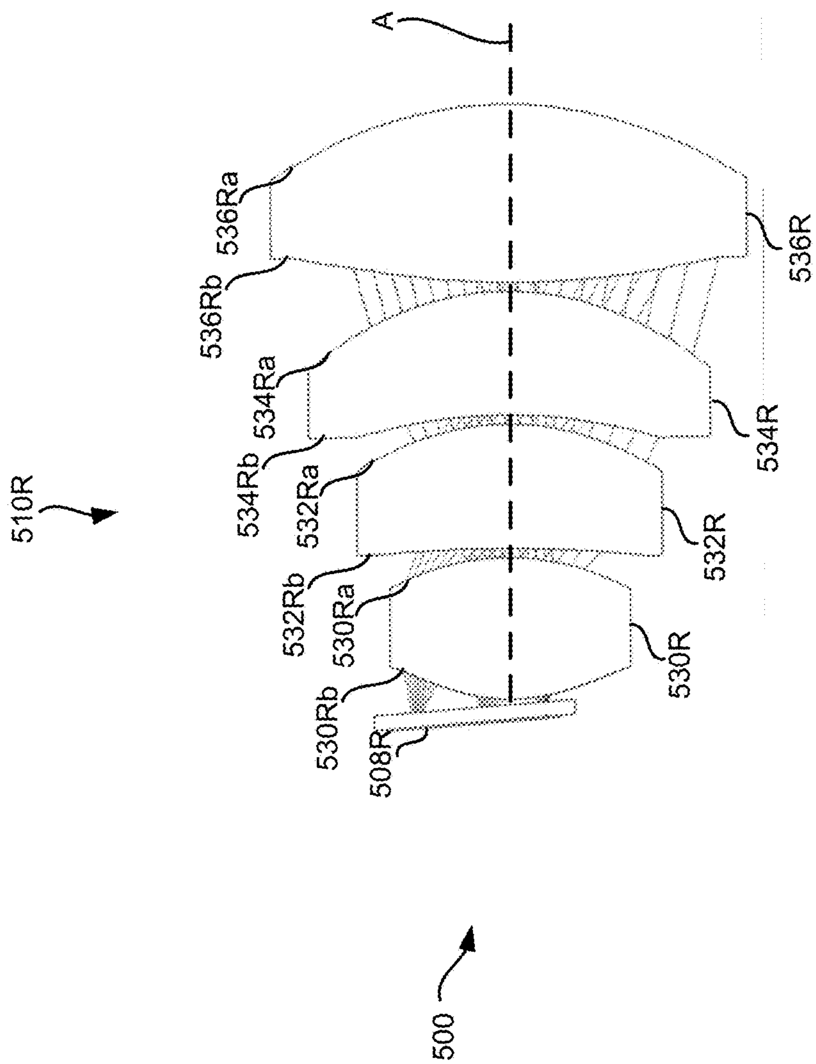

510R
A
536Ra
536Rb
536R
534Ra
534Rb
534R
532Ra
532Rb
532R
530Ra
530Rb
530R
508R
500

FIG. 6

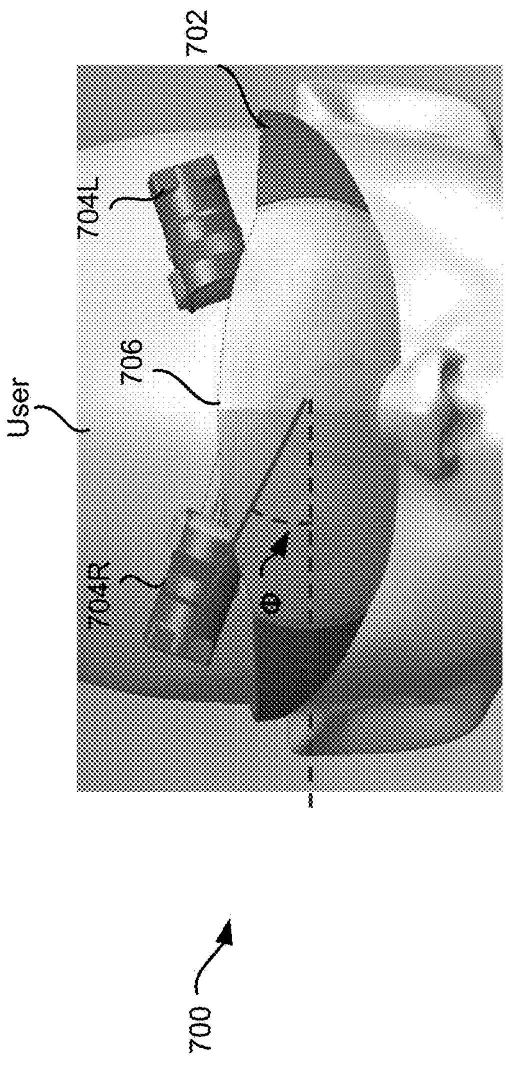


FIG. 7

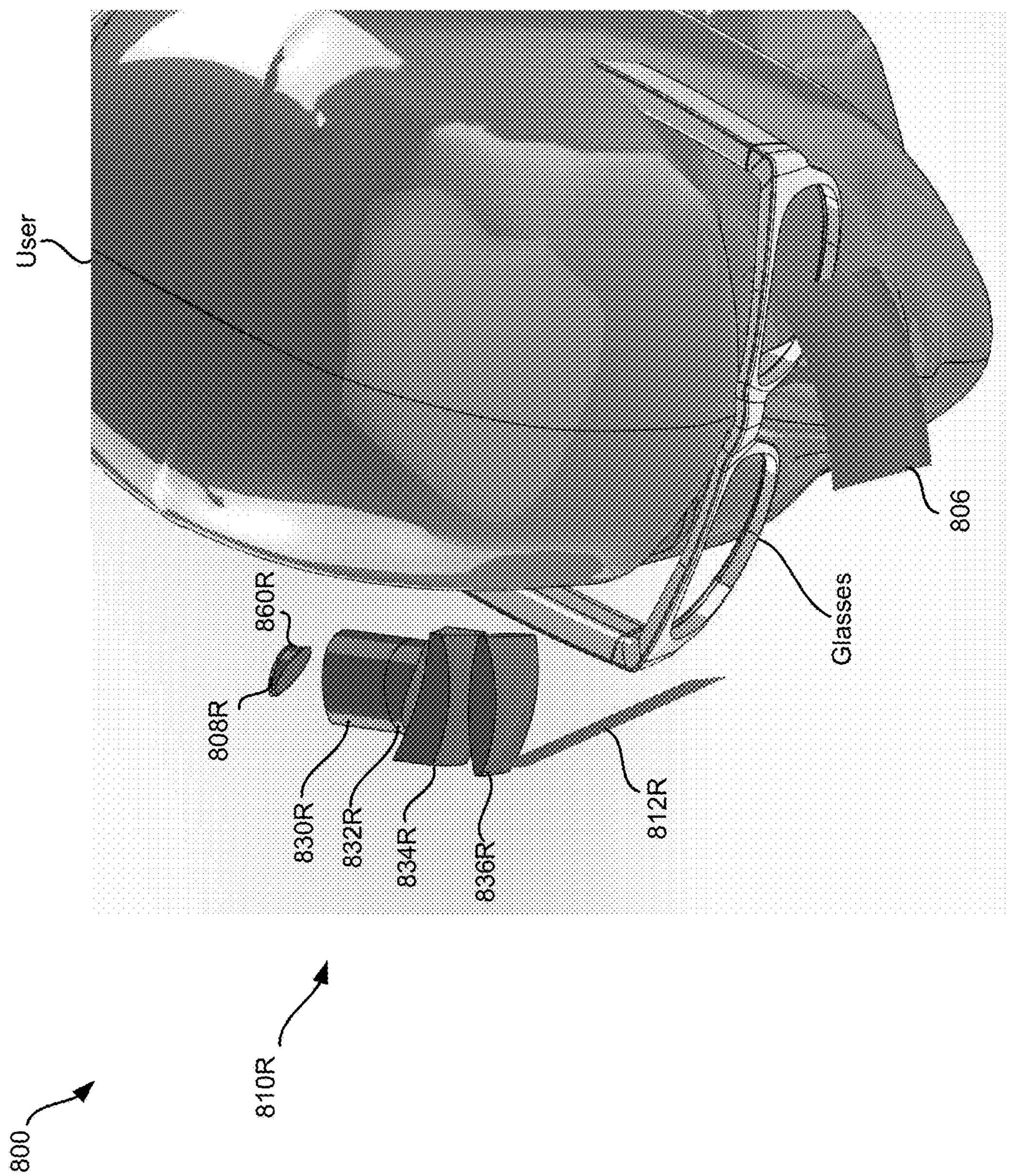


FIG. 8A

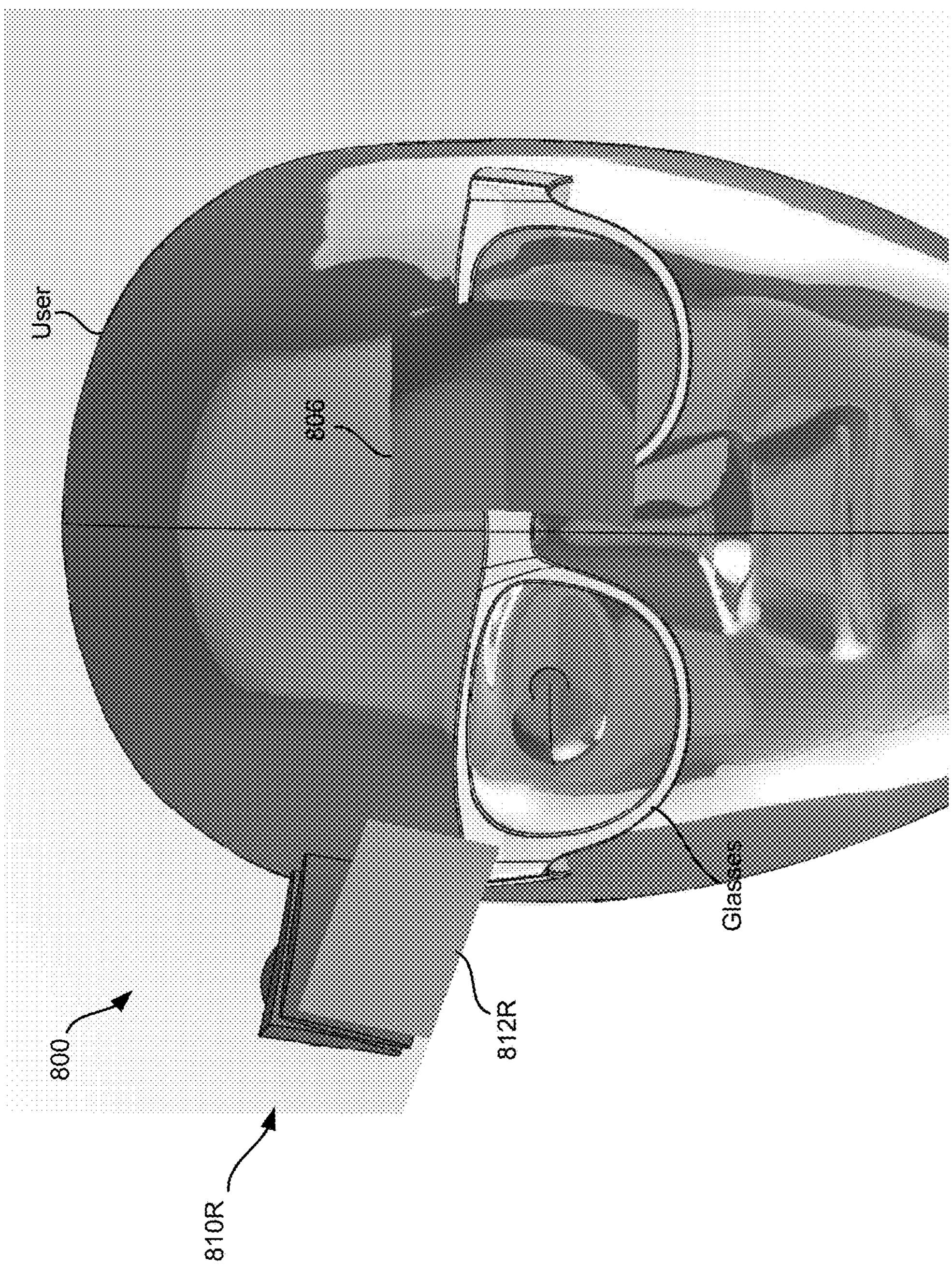


FIG. 8B

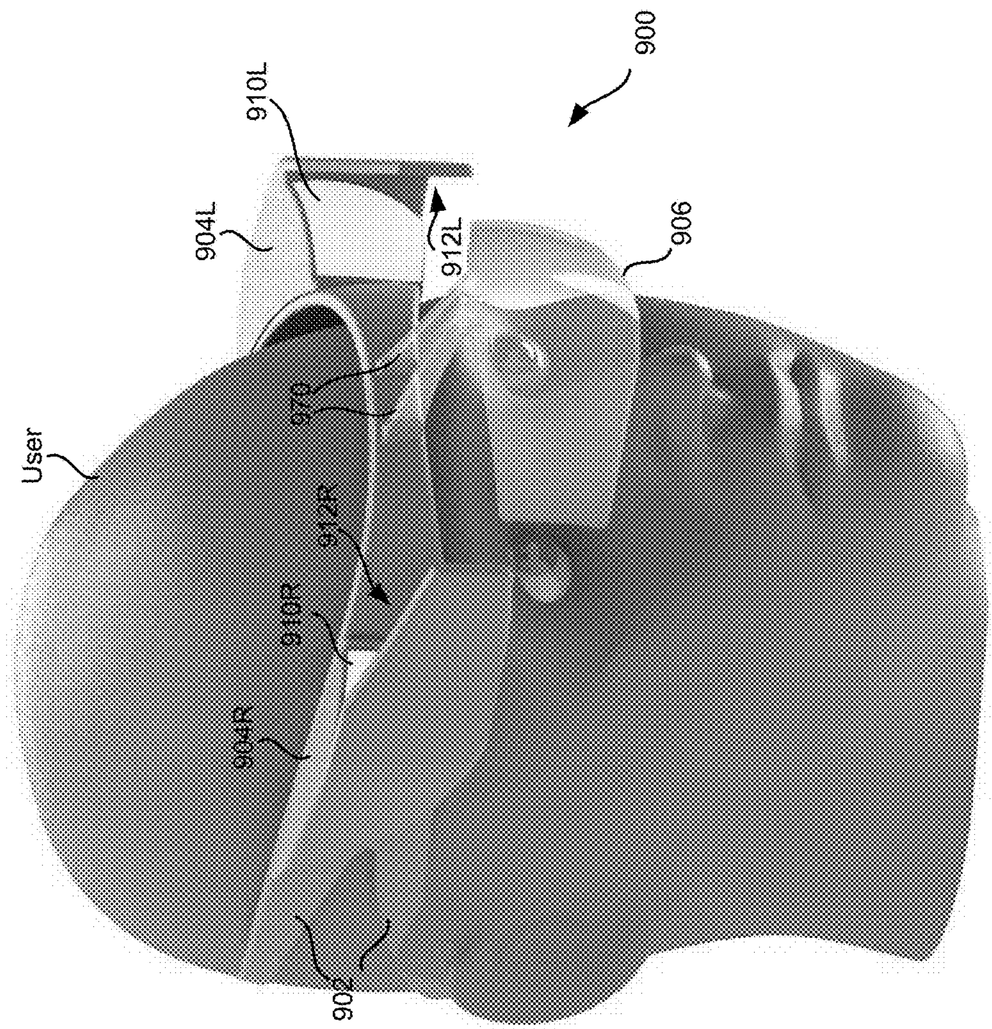


FIG. 9A

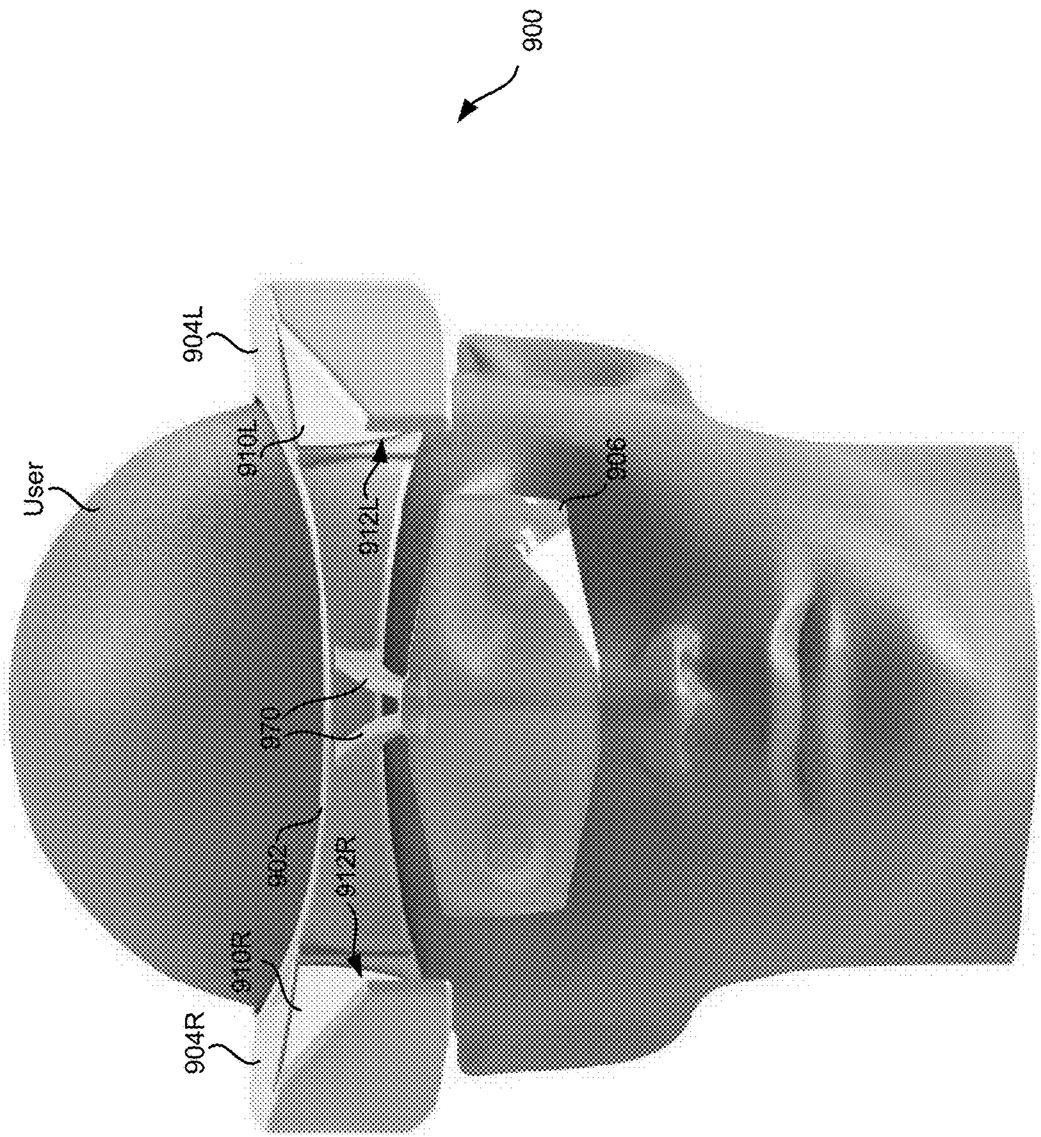


FIG. 9B

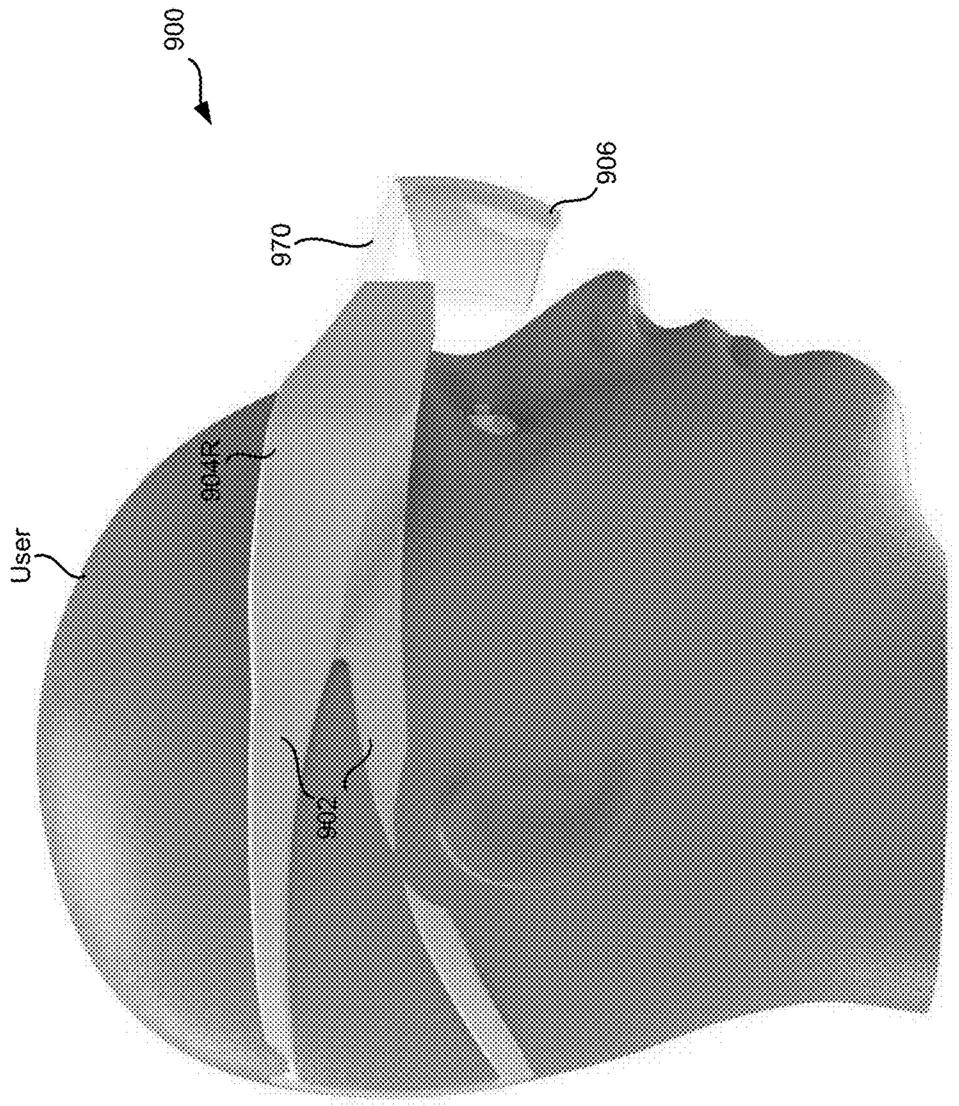


FIG. 9C

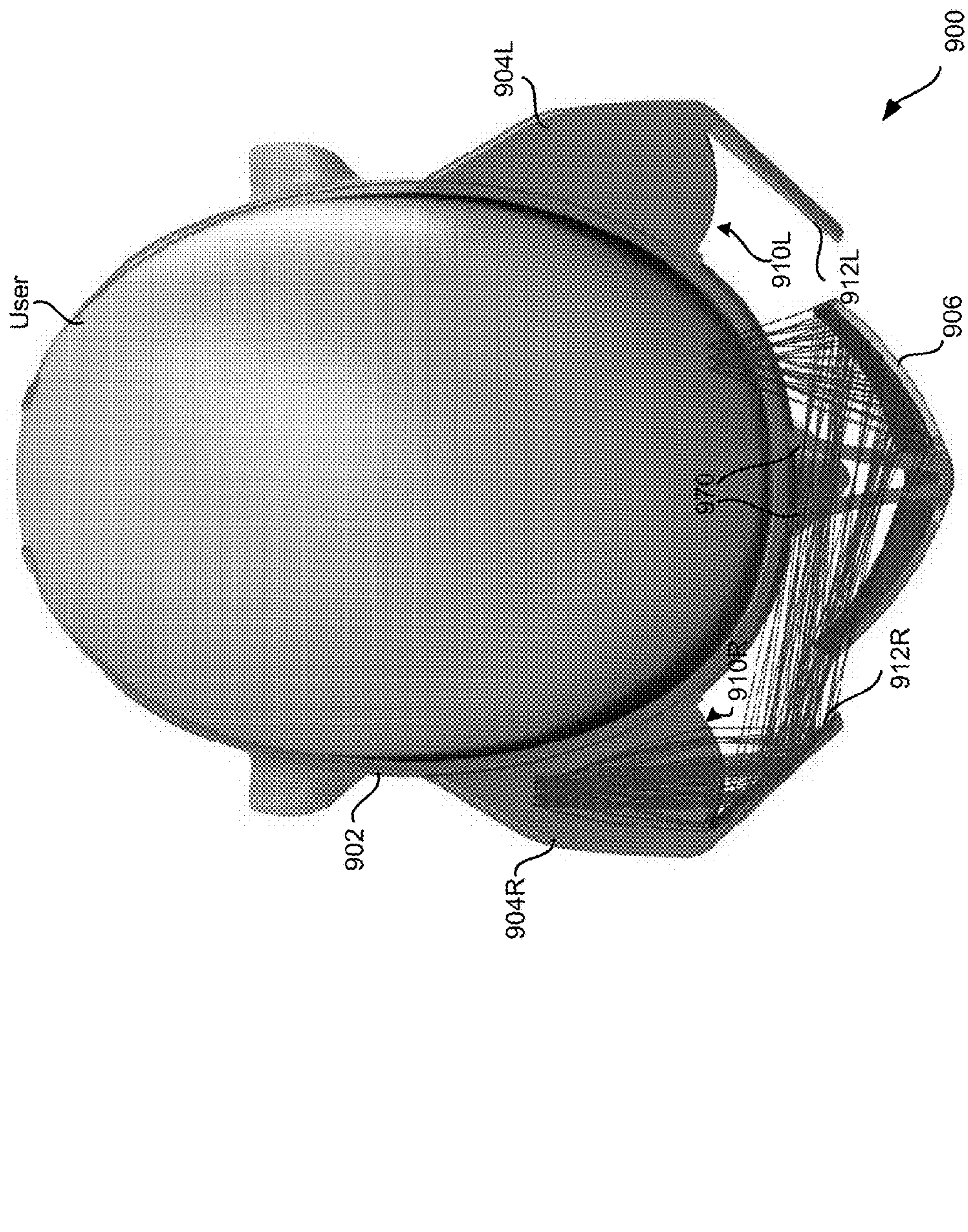
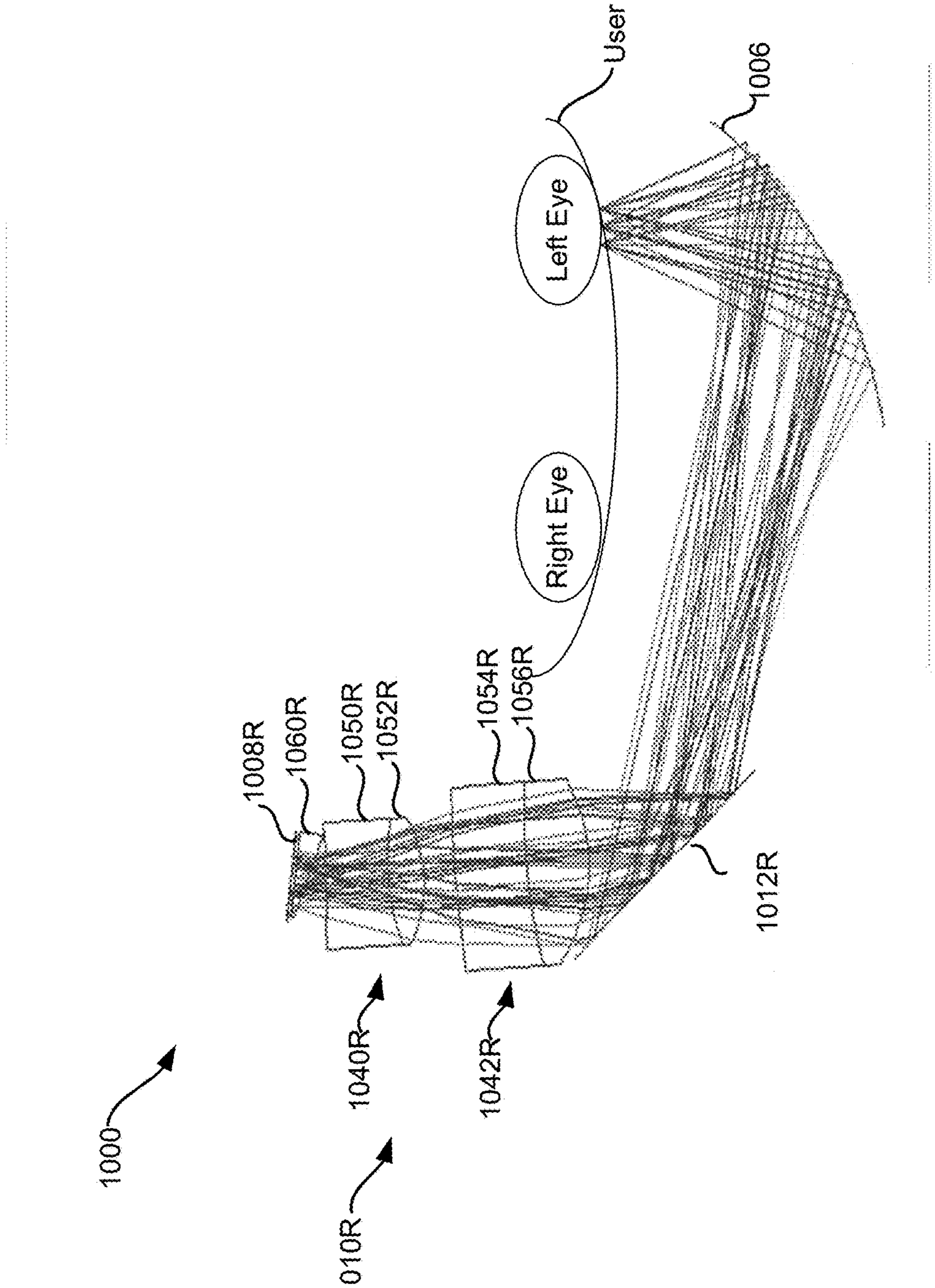


FIG. 9D



User
1006
Left Eye
Right Eye
1054R
1056R
1008R
1060R
1050R
1052R
1012R
1000
1040R
1042R
1010R

FIG. 10

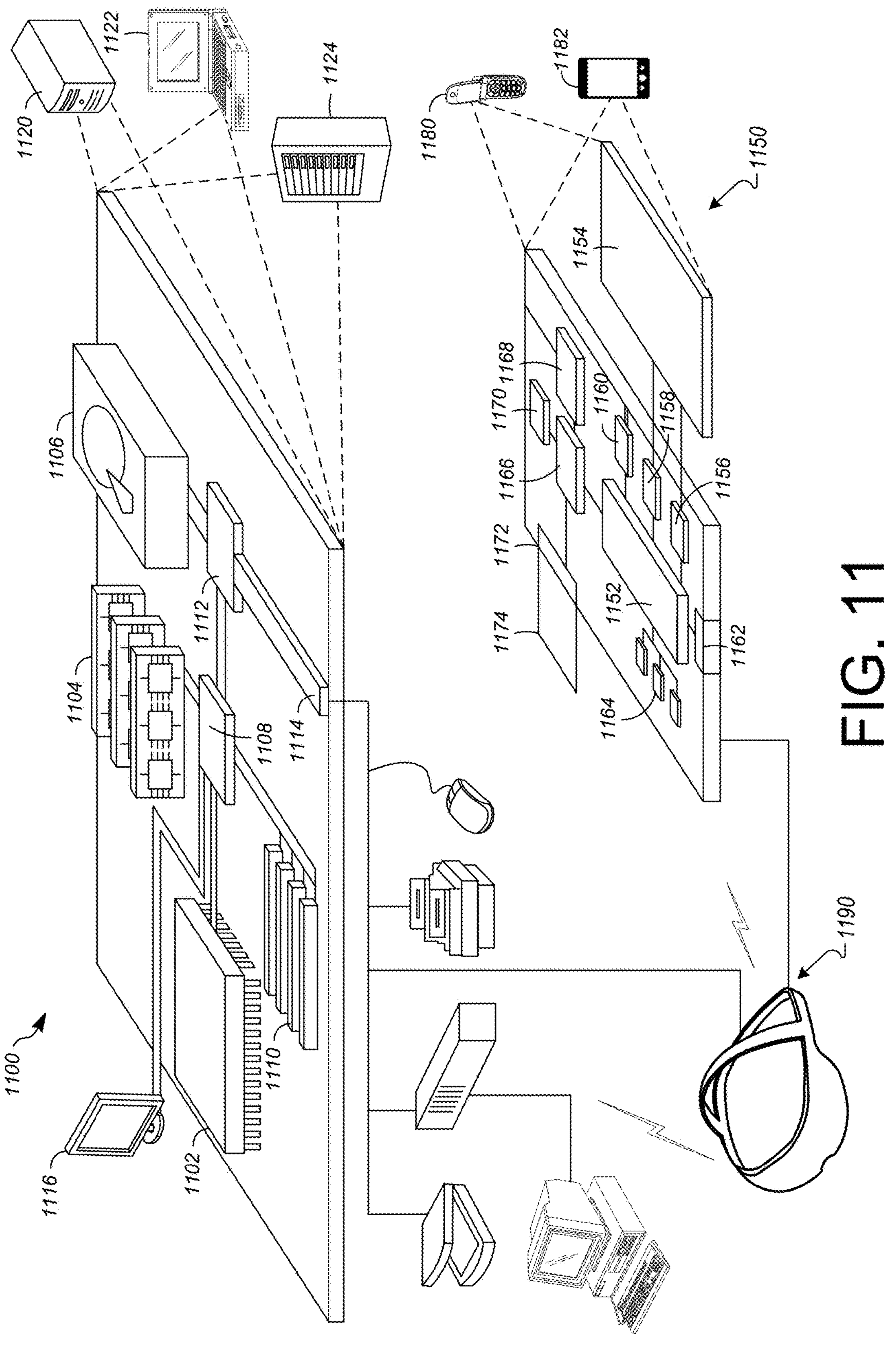

1100
1102
1104
1106
1108
1110
1112
1114
1116
1120
1122
1124
1150
1152
1154
1156
1158
1160
1162
1164
1166
1168
1170
1172
1174
1180
1182
1190

FIG. 11

HEAD-WORN AUGMENTED REALITY DISPLAY

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Application No. 62/566,182, filed Sep. 29, 2017, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] An augmented reality (AR) system can generate an immersive augmented environment for a user. The immersive augmented environment can be generated by superimposing computer-generated content on a user's field of view of the real world. For example, the computer-generated content can include labels, textual information, images, sprites, and three-dimensional entities.

[0003] These images may be displayed at a position in the user's field of view so as to appear to overlay an object in the real world. An AR system may include a head-mounted display (HMD) that can overlay the computer-generated images on the user's field of view.

SUMMARY

[0004] This disclosure relates to a head-worn augmented reality display. In a non-limiting example, the head-worn augmented reality display may include a combiner, which may have a positive wrap angle. The head-worn augmented reality display may also include a microdisplay device that emits image content that is intended to cross in front of a user's face and intersect with the combiner. For example, the microdisplay device may be configured to be positioned on or towards the left side of the user's face when the head-worn augmented reality display is being worn and to project image content that crosses in front of the user's face and intersects with the combiner in the field of view of the user's right eye, so that the image content is visible to the right eye. Another microdisplay device may also be provided in the opposite sense, positioned on or towards the right side of the user's face to project the same or different image content for intersecting with the combiner in the field of view of the user's left eye so that this image content is visible to the left eye.

[0005] One aspect is a head-mounted display device, comprising: a frame having a structure that is configured to be worn by a user; a combiner that is attached to the frame and includes a curved transparent structure having a reflective surface; and a microdisplay device attached to the frame and configured to, when the frame is worn by the user, emit image content that crosses in front of the user's face and intersects with the reflective surface of the combiner.

[0006] Another aspect is an augmented reality head-mounted display device, comprising: a frame having a structure that is configured to be worn by a user; a combiner that is attached to the frame and has an inner surface and an outer surface, the inner surface being reflective and the outer surface having a positive wrap angle; and a microdisplay device attached to the frame and configured to, when the frame is worn by the user, emit image content that intersects with the inner surface of the combiner.

[0007] Yet another aspect is a head-mounted display device, comprising: a frame having a structure that is configured to be worn by a user, the frame including a left arm configured to rest on the user's left ear and a right arm configured to rest on the user's right ear; a combiner that is attached to the frame and includes a curved transparent structure that has an inner surface and an outer surface, the inner surface being reflective; a left microdisplay device attached to the frame and configured to emit image content for the user's right eye, the left microdisplay device emitting image content so that the image content crosses in front of the user's face and intersects with the inner surface of the combiner; and a right microdisplay device attached to the frame and configured to emit image content for the user's left eye, the right microdisplay device emitting image content so that the image content crosses in front of the user's face and intersects with the inner surface of the combiner.

[0008] The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a block diagram illustrating a system according to an example implementation.

[0010] FIG. **2** is a third person view of an example physical space, in which a user is experiencing an AR environment through an example HMD, in accordance with implementations as described herein.

[0011] FIG. **3** is a schematic diagram of an example HMD, in accordance with implementations as described herein.

[0012] FIGS. **4**A and **4**B are schematic diagrams of an example HMD, in accordance with implementations as described herein.

[0013] FIG. **5** is a schematic diagram of a portion of an example HMD, in accordance with implementations as described herein.

[0014] FIG. **6** is another schematic diagram of a portion of the example HMD, in accordance with implementations as described herein.

[0015] FIG. **7** is a schematic diagram of a portion of an example HMD, in accordance with implementations as described herein.

[0016] FIGS. **8**A and **8**B show a schematic diagram of another example implementation of an HMD being worn over glasses by a user, in accordance with implementations as described herein.

[0017] FIGS. **9**A-**9**D show a schematic diagram of another example implementation of an HMD being worn by a user, in accordance with implementations as described herein.

[0018] FIG. **10** is a schematic diagram of a portion of an example HMD, in accordance with implementations as described herein.

[0019] FIG. **11** shows an example of a computing device and a mobile computing device that can be used to implement the techniques described herein.

DETAILED DESCRIPTION

[0020] Reference will now be made in detail to non-limiting examples of this disclosure, examples of which are illustrated in the accompanying drawings. The examples are described below by referring to the drawings, wherein like reference numerals refer to like elements. When like reference numerals are shown, corresponding description(s) are not repeated and the interested reader is referred to the previously discussed figure(s) for a description of the like element(s).

[0021] At least some implementations of AR systems include a head-mounted display device (HMD) that can be worn by a user. The HMD may display images that cover a portion of a user's field of view. Some implementations of an HMD include a frame that can be worn by the user, a microdisplay device that can generate visual content, and a combiner that overlays the visual content generated by the microdisplay device on the user's field of view of the physical environment. In this manner, the visual content generated by the microdisplay augments the reality of the user's physical environment.

[0022] In some implementations, the HMD also includes a lens assembly that forms an intermediary image from or otherwise alters light beams of the visual content generated by the microdisplay device. Implementations of the HMD may also include a fold mirror to reflect or redirect light beams associated with the visual content generated by the microdisplay device.

[0023] The HMD may be configured to overlay computer-generated visual content over the field of view of one or both of the user's eyes. In at least some embodiments, the HMD includes a first microdisplay device that is disposed on a first side of the user's head (e.g., the left side) and is configured to overlay computer-generated visual content over the field of view of the eye on the opposite side (e.g., the right eye) when the HMD is worn. The HMD may also include a second microdisplay device the is disposed on the second side of the user's head (e.g., the right side) and is configured to overlay computer-generated visual content over the field of view of the eye on the opposite side (e.g., the left eye) when the HMD is worn.

[0024] For example, the placement of a microdisplay device on the side of the user's head opposite to the eye upon which the microdisplay overlays content may allow the HMD to be formed with a positive wrap angle combiner. A positive wrap angle combiner may allow for a more aesthetic HMD. For example, the HMD may have a visor-like style in which the front of the HMD has a single smooth convex curvature. For example, having an HMD having a smooth curvature includes an HMD having a curvature with a continuous first derivative. The combiner may have an outer surface that is opposite the reflective surface (e.g., on the opposite side of a thin plastic structure). An HMD having a convex curvature includes an HMD having an outer surface with a convex curvature. A positive wrap angle for the combiner may, for example, be understood as the combiner generally wrapping around the front of the user's head or face, or having a center of curvature generally located towards rather than away from the user's head. In some implementations, the center of curvature for all or substantially all segments of the combiner is located towards rather than away from the user's head.

[0025] In some implementations, the positive wrap angle visor includes two separate regions (i.e., not having a continuous curvature) of the combiner that meet at an angle that is less than 180 degrees in front of the user's nose (i.e., both regions are angled/tilted in towards the user's temples). For example, a positive wrap angle visor may not have any indents or concave regions in front of the user's eyes when viewed from in front of the user (e.g., the outer surface of the combiner does not have any indents or concavities). In some implementations, a positive wrap angle visor includes a combiner having a midpoint that when worn by a user is more anterior than any other part of the combiner. In contrast, an HMD with a negative-wrap angle combiner may have a bug eyed shape in which the HMD bulges out separately in front of each of the user's eyes. For example, a negative-wrap angle combiner may have one or more indents or concave regions on the combiner, such as a concave region disposed on the combiner at a location that would be in front of a midpoint between a user's eyes when the HMD is being worn.

[0026] FIG. **1** is a block diagram illustrating a system **100** according to an example implementation. The system **100** generates an augmented reality (AR) environment for a user of the system **100**. In some implementations, the system **100** includes a computing device **102**, a head-mounted display device (HMD) **104**, and an AR content source **106**. Also shown is a network **108** over which the computing device **102** may communicate with the AR content source **106**.

[0027] The computing device **102** may include a memory **110**, a processor assembly **112**, a communication module **114**, and a sensor system **116**. The memory **110** may include an AR application **118**, AR content **120**, and a content warper **122**. The computing device **102** may also include various user input components (not shown) such as a controller that communicates with the computing device **102** using a wireless communications protocol. In some implementations, the computing device **102** is a mobile device (e.g., a smart phone) which may be configured to provide or output AR content to a user via the HMD **104**. For example, the computing device **102** and the HMD **104** may communicate via a wired connection (e.g., a Universal Serial Bus (USB) cable) or via a wireless communication protocol (e.g., any WiFi protocol, any BlueTooth protocol, Zigbee, etc.). Additionally or alternatively, the computing device **102** is a component of the HMD **104** and may be contained within a housing of the HMD **104** or included with the HMD **104**.

[0028] The memory **110** can include one or more non-transitory computer-readable storage media. The memory **110** may store instructions and data that are usable to generate an AR environment for a user.

[0029] The processor assembly **112** includes one or more devices that are capable of executing instructions, such as instructions stored by the memory **110**, to perform various tasks associated with generating an AR environment. For example, the processor assembly **112** may include a central processing unit (CPU) and/or a graphics processing unit (GPU). For example, if a GPU is present, some image/video rendering tasks may be offloaded from the CPU to the GPU.

[0030] The communication module **114** includes one or more devices for communicating with other computing devices, such as the AR content source **106**. The communication module **114** may communicate via wireless or wired networks, such as the network **108**.

[0031] The sensor system **116** may include various sensors, such as an inertial motion unit (IMU) **124**. Implementations of the sensor system **116** may also include different types of sensors, including, for example, a light sensor, an audio sensor, an image sensor, a distance and/or proximity sensor, a contact sensor such as a capacitive sensor, a timer, and/or other sensors and/or different combination(s) of sensors. In some implementations, the AR application may use the sensor system **116** to determine a location and orientation of a user within a physical environment and/or to recognize features or objects within the physical environments.

[0032] The IMU **124** detects motion, movement, and/or acceleration of the computing device **102** and/or the HMD **104**. The IMU **124** may include various different types of sensors such as, for example, an accelerometer, a gyroscope, a magnetometer, and other such sensors. A position and orientation of the HMD **104** may be detected and tracked based on data provided by the sensors included in the IMU **124**. The detected position and orientation of the HMD **104** may allow the system to detect and track the user's gaze direction and head movement.

[0033] The AR application **118** may present or provide the AR content to a user via the HMD and/or one or more output devices of the computing device **102** such as a display device, a speaker, and/or other output devices. In some implementations, the AR application **118** includes instructions stored in the memory **110** that, when executed by the processor assembly **112**, cause the processor assembly **112** to perform the operations described herein. For example, the AR application **118** may generate and present an AR environment to the user based on, for example, AR content, such as the AR content **120** and/or AR content received from the AR content source **106**. The AR content **120** may include content such as images or videos that may be displayed on a portion of the user's field of view in the HMD **104**. For example, the content may include annotations of objects and structures of the physical environment in which the user is located. The content may also include objects that overlay various portions of the physical environment. The content may be rendered as flat images or as three-dimensional (3D) objects. The 3D objects may include one or more objects represented as polygonal meshes. The polygonal meshes may be associated with various surface textures, such as colors and images. The AR content **120** may also include other information such as, for example, light sources that are used in rendering the 3D objects.

[0034] The AR application **118** may use the content warper **122** to generate images for display via the HMD **104** based on the AR content **120**. In some implementations, the content warper **122** includes instructions stored in the memory **110** that, when executed by the processor assembly **112**, cause the processor assembly **112** to warp an image or series of images prior to being displayed via the HMD **104**. For example, the content warper **122** may warp images that are transmitted to the HMD **104** for display so as to counteract a warping caused by a lens assembly of the HMD **104**. In some implementations, the content warper corrects a specific aberration, namely distortion, which changes the shape of the image but does not blur the images.

[0035] The AR application **118** may update the AR environment based on input received from the IMU **124** and/or other components of the sensor system **116**. For example, the IMU **124** may detect motion, movement, and/or acceleration of the computing device **102** and/or the HMD **104**. The IMU **124** may include various different types of sensors such as, for example, an accelerometer, a gyroscope, a magnetometer, and other such sensors. A position and orientation of the HMD **104** may be detected and tracked based on data provided by the sensors included in the IMU **124**. The detected position and orientation of the HMD **104** may allow the system to in turn, detect and track the user's position and orientation within a physical environment. Based on the detected position and orientation, the AR application **118** may update the AR environment to reflect a changed orientation and/or position of the user within the environment.

[0036] Although the computing device **102** and the HMD **104** are shown as separate devices in FIG. **1**, in some implementations, the computing device **102** may include the HMD **104**. In some implementations, the computing device **102** communicates with the HMD **104** via a cable, as shown in FIG. **1**. For example, the computing device **102** may transmit video signals and/or audio signals to the HMD **104** for display for the user, and the HMD **104** may transmit motion, position, and/or orientation information to the computing device **102**.

[0037] The AR content source **106** may generate and output AR content, which may be distributed or sent to one or more computing devices, such as the computing device **102**, via the network **108**. In an example implementation, the AR content includes three-dimensional scenes and/or images. The three-dimensional scenes may incorporate physical entities from the environment surrounding the HMD **104**. Additionally, the AR content may include audio/video signals that are streamed or distributed to one or more computing devices. The AR content may also include an AR application that runs on the computing device **102** to generate 3D scenes, audio signals, and/or video signals.

[0038] The network **108** may be the Internet, a local area network (LAN), a wireless local area network (WLAN), and/or any other network. A computing device **102**, for example, may receive the audio/video signals, which may be provided as part of AR content in an illustrative example implementation, via the network.

[0039] FIG. **2** is a third person view of an example physical space **200**, in which a user is experiencing an AR environment **202** through the example HMD **104**. The AR environment **202** is generated by the AR application **118** of the computing device **102** and displayed to the user through the HMD **104**.

[0040] The AR environment **202** includes an annotation **204** that is displayed in association with an entity **206** in the physical space **200**. In this example, the entity **206** is a flower in a pot and the annotation **204** identifies the flower and provides care instructions. The annotation **204** is displayed on the user's field of view by the HMD **104** so as to overlay the user's view of the physical space **200**. For example, portions of the HMD **104** may be transparent, and the user may be able to see the physical space **200** through those portions while the HMD **104** is being worn.

[0041] FIG. **3** is a schematic diagram of an example HMD **300**. The HMD **300** is an example of the HMD **104** of FIG. **1**. In some implementations, the HMD **300** includes a frame **302**, a housing **304**, and a combiner **306**.

[0042] The frame **302** is a physical component that is configured to be worn by the user. For example, the frame **302** may be similar to a glasses frame. For example, the frame **302** may include arms with ear pieces and a bridge with nose pieces.

[0043] The housing **304** is attached to the frame **302** and may include a chamber that contains components of the HMD **300**. The housing **304** may be formed from a rigid material such as a plastic or metal. In some implementations, the housing **304** is positioned on the frame **302** so as to be adjacent to a side of the user's head when the HMD **300** is worn. In some implementations, the frame **302** includes two housings such that one housing is positioned on each side of the user's head when the HMD **300** is worn. For example, a first housing may be disposed on the left arm of the frame **302** and configured to generate images that overlay the field of view of the user's right eye and a second housing may be disposed on the right arm of the frame **302** and configured to generate images that overlay the field of view of the user's left eye.

[0044] The housing **304** may contain a microdisplay device **308**, a lens assembly **310**, and a fold mirror assembly **312**. The microdisplay device **308** is an electronic device that displays images. The microdisplay device **308** may include various microdisplay technologies such as Liquid Crystal Display (LCD) technology, including Liquid Crystal on Silicon (LCOS), Ferroelectric Liquid Crystal (FLCoS), Light Emitting Diode (LED) technology, and/or Organic Light Emitting Diode (OLED) technology.

[0045] The lens assembly **310** is positioned in front of the microdisplay device **308** and forms an intermediary image between the lens assembly **310** and combiner **306** from the light emitted by the microdisplay device **308** when the microdisplay device **308** displays images. The lens assembly **310** may include one or more field lenses. For example, the lens assembly **310** may include four field lenses. In some implementations, the field lenses are oriented along a common optical axis. In other implementations, at least one of the field lenses is oriented along a different optical axis than the other field lenses. The lens assembly **310** may distort the images generated by the microdisplay device **308** (e.g., by altering light of different colors in different ways). In some implementations, the images displayed by the microdisplay device **308** are warped (e.g., by the content warper **122**) to counteract the expected alterations caused by the lens assembly **310**.

[0046] Some implementations include a fold mirror assembly **312**. The fold mirror assembly **312** may reflect the light emitted by the microdisplay device **308**. For example, the fold mirror assembly **312** may reflect light that has passed through the lens assembly **310** by approximately 90 degrees. For example, when the HMD **300** is worn by a user, the light emitted by the microdisplay device **308** may initially travel along a first side of the user's head toward the front of the user's head, where the light is then reflected 90 degrees by the fold mirror assembly **312** to travel across and in front of the user's face towards a portion of the combiner **306** disposed in front of the user's opposite eye.

[0047] The combiner **306** is a physical structure that allows the user to view a combination of the physical environment and the images displayed by the microdisplay device **308**. For example, the combiner **306** may include a curved transparent structure that includes a reflective coating. The curved transparent structure may be formed from a plastic or another material. The reflective coating may reflect the light emitted by the microdisplay device **308** and reflected by the fold mirror assembly **312** toward the user's eye over the user's field of view of the physical environment through the combiner **306**. The reflective coating may be configured to transmit light from the physical environment (e.g., behind the combiner **306**). For example, a user may be able to look through the reflective coating to see the physical environment. In some implementations, the reflective coating is transparent when light is not directed at the coating (e.g., light from the microdisplay device **308**) or allows light to pass through even when light is being reflected. In this manner, the combiner **306** will combine the reflected light from the display with the transmitted light from the physical environment (i.e., the real world) to, for example, generate a combined image that is perceived by at least one of a wearer's eyes). In some implementations, the combiner **306** may have a smooth, curved structure that is free of inflection points and extrema.

[0048] In some implementations, when the HMD **300** is worn, the combiner **306** reflects light emitted by a microdisplay device **308** located on one side of a person's face into the field of an eye on the other side of the person's face. For example, the light (or image content) emitted by the microdisplay device **308** may cross in front of the user's face before reflecting off of the combiner **306** toward the user's eye. As an example, crossing in front of the user's face may include crossing the sagittal plane of the user's face. The sagittal plane is an imaginary vertical plane that divides a person into a left half and a right half. The sagittal plane of a user's face runs between the user's eyes.

[0049] Although this example HMD **300** includes a fold mirror assembly **312**, some implementations of the HMD **300** do not include a fold mirror assembly. For example, the microdisplay device **308** may be disposed so as to emit light that travels in front of and across the user's face and contacts the combiner **306** (after passing through the lens assembly **310**).

[0050] In some implementations, the HMD **300** may include additional components that are not shown in FIG. **3**. For example, the HMD **300** may include an audio output device including, for example, speakers mounted in headphones, that are coupled to the frame **302**.

[0051] In some implementations, the HMD **300** may include a camera to capture still and moving images. The images captured by the camera may be used to help track a physical position of the user and/or the HMD **300** in the real world, or physical environment. For example, these images may be used to determine the content of and the location of content in the augmented reality environment generated by the HMD **300**.

[0052] The HMD **300** may also include a sensing system that includes an inertial measurement unit (IMU), which may be similar to the IMU **124** of FIG. **1**. A position and orientation of the HMD **300** may be detected and tracked based on data provided by the sensing system. The detected position and orientation of the HMD **300** may allow the system to detect and track the user's head gaze direction and movement.

[0053] In some implementations, the HMD **300** may also include a gaze tracking device to detect and track an eye gaze of the user. The gaze tracking device may include, for example, one or more image sensors positioned to capture images of the user's eyes. These images may be used, for example, to detect and track direction and movement of the user's pupils. In some implementations, the HMD **300** may be configured so that the detected gaze is processed as a user input to be translated into a corresponding interaction in the AR experience.

[0054] Various implementations of the systems and techniques described here can be realized in digital electronic circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

[0055] These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the terms “machine-readable medium” and “computer-readable medium” refer to any computer program product, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term “machine-readable signal” refers to any signal used to provide machine instructions and/or data to a programmable processor.

[0056] Some implementations of the HMD **300** also include a handheld electronic device that can communicatively couple (e.g., via a wired or wireless connection) to the HMD **300**. The handheld electronic device may allow the user to provide input to the HMD **300**. The handheld electronic device may include a housing with a user interface on an outside of the housing that is accessible to the user. The user interface may include a touch sensitive surface that is configured to receive user touch inputs. The user interface may also include other components for manipulation by the user such as, for example, actuation buttons, knobs, joysticks and the like. In some implementations, at least a portion of the user interface may be configured as a touchscreen, with that portion of the user interface being configured to display user interface items to the user, and also to receive touch inputs from the user on the touch sensitive surface.

[0057] The HMD **300** can also include other kinds of devices to provide for interaction with a user; for example, feedback provided to the user can be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback); and input from the user can be received in any form, including acoustic, speech, or tactile input.

[0058] FIG. **4**A is a schematic diagram of an example HMD **400**. The HMD **400** is an example of the HMD **104**. In this example, the HMD **400** includes a frame **402**, a left housing **404**L, a right housing **404**R, and a combiner **406**. The frame **402** may be similar to the frame **302**, the left housing **404**L and the right housing **404**R may be similar to the housing **304**, the combiner **406** may be similar to the combiner **306**.

[0059] The housing **404**L contains a microdisplay device **408**L and a lens assembly **410**L. Similarly, the housing **404**R contains a microdisplay device **408**R and a lens assembly **410**R. The microdisplay devices **408**L and **408**R may be similar to the microdisplay device **308**, and the lens assemblies **410**L and **410**R may be similar to the lens assembly **310**. In this example, the microdisplay device **408**R emits content **420**R as light, which passes through the lens assembly **410**R and then crosses the user’s face to reflect off of the combiner **406** towards the user’s left eye. The content **420**R reflects off of the combiner **406** at a position that is approximately in front of the user’s left eye. Similarly, the microdisplay device **408**L emits light L**2** that passes through the lens assembly **410**L and the crosses the user’s face to reflect off of the combiner **406** toward the user’s right eye. The content **420**L reflects off of the combiner **406** at a position that is approximately in front of the user’s right eye. In this manner, the content emitted on each side of the user’s face is ultimately projected onto the field of view of the user’s opposite eye. In this example, the housings **404**R and **404**L do not include fold mirror assemblies as the microdisplay devices **408**L and **408**R are directed toward the combiner **406**.

[0060] FIG. **4**B is a schematic diagram of the example HMD **400** that illustrates a positive wrap angle. A midpoint **480** of the combiner **406** is shown. When the HMD **400** is worn by the user, the midpoint **480** is disposed on the sagittal plane of the user. In this example, the HMD **400** has a positive wrap angle. For example, the combiner **406** is slanted (or curved) from the midpoint **480** in the posterior direction. As shown in this figure, the further the frame curves back toward the posterior direction the greater the positive wrap angle. In this example, the combiner **406** of the HMD has a positive wrap angle of at least 20 degrees. In some implementations, when an HMD with a positive wrap angle is worn, the midpoint **480** is the most anterior point on the combiner **406**.

[0061] In contrast, an HMD with a negative wrap angle would be angled (or curved) out from the midpoint **480** in the anterior direction (i.e., away from the user’s face). An HMD with a negative wrap angle may have a “bug-eyed” appearance.

[0062] FIG. **5** is a schematic diagram of a portion of an example HMD **500**. The HMD **500** is an example of the HMD **104**. In this example, the HMD **500** includes a right microdisplay device **508**R, a right lens assembly **510**R, and a combiner **506**. The right microdisplay device **508**R may be similar to the microdisplay device **308**, the right lens assembly **510**R may be similar to the lens assembly **310**, and the combiner **506** may be similar to the combiner **306**. In this example, the combiner **506** is tilted appropriately to direct the light toward the user’s eye and to maintain a positive wrap angle. For example, in some implementations, the combiner **506** is tilted so as to reflect light travelling along the optical axis A by 38.5 degrees with respect to a bisector (as indicated at Θ). As described elsewhere, the combiner **506** may also be tilted in an upward direction by, for example, 12 degrees or approximately 12 degrees to clear eyeglasses worn by the user.

[0063] In some implementations, the shape of the combiner **506** can be described using the following equation:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{j=2}^{66} C_j x^m y^n$$

$$j = \frac{(m+n)^2 + m + 3n}{2} + 1$$

and the following coefficients:

[0064] X2: −1.2071E-02
[0065] XY: 3.4935E-03
[0066] Y2: −7.6944E-03
[0067] X2Y: 6.3336E-06
[0068] Y3: 1.5369E-05
[0069] X2Y2: −2.2495E-06
[0070] Y4: −1.3737E-07

[0071] These equations and coefficients are just examples. Other implementations may include a combiner with a surface defined by different equations and coefficients.

[0072] In this example, the right lens assembly **510**R includes a first right field lens **530**R, a second right field lens **532**R, a third right field lens **534**R, and a fourth right field lens **536**R. In the implementation shown in FIG. **5**, the first right field lens **530**R, the second right field lens **532**R, the third right field lens **534**R, and the fourth right field lens **536**R are all oriented along the optical axis A.

[0073] In this example, the microdisplay device **508**R emits content **520**R as light, which passes through the lens assembly **510**R and then crosses the user's face to reflect off of the combiner **506** towards the user's left eye. As can be seen in the figure, the content **520**R is composed of light of different colors (wavelengths). The tilted and off-axis nature of the system may lead to distortion/warping of the content **520**R. An off-axis system may, for example, include at least one bend in the optical path of the content **520**R. An example of an off-axis system is a system in which not all of the components of the system are along an axis aligned with the target (e.g., the user's eye). An example of an off-axis system includes a system in which the content **520**R is refracted. As noted, the content **520**R may be warped (e.g., by the content warper **122**) prior to emission to counteract this warping by the lens assembly **510**R. In various implementations, the field lenses of the lens assembly **510**R can be made of various materials. In some implementations, all of the field lenses are made of the same type of material; while in other implementations, at least one of the field lenses is made from a different type of material than the other field lenses.

[0074] Although the HMD **500** is shown as including the components to present the content **520**R to the user's left eye, some embodiments also include components to present content to the user's right eye. For example, the content **520**R emitted on the right side of the user's head and the content emitted on the left side of the user's head may cross one another in front of the user's head.

[0075] FIG. **6** is another schematic diagram of a portion of the example HMD **500**. In some implementations, the field lenses balance (or reduce) astigmatism from the combiner **506** and perform color correction. The lenses may be formed from materials that have different Abbe numbers. For example, the field lenses of the lens assembly **510**R may be formed from glass or polymer materials. In some implementations, at least one of the field lenses is formed from a second material having an Abbe number equal to or approximately equal to 23.9, such as a polycarbonate resin, an example of which is available under the brand name Lupizeta® EP-5000 from Mitsubishi Gas Chemical Company, Inc. In some implementations, at least one of the field lenses is formed from a first material having an Abbe number equal to or approximately equal to 56, such as a cyclo olefin polymer (COP) material, an example of which is available under the brand name Zeonex® Z-E48R from Zeon Specialty Materials, Inc. In some implementations, the first right field lens **530**R is formed from the first material, and the remaining field lenses **532**R, **534**R, and **536**R are formed from the second material. Alternatively, a single material is used for all of the field lenses in combination with a diffractive optical element to achieve color correction.

[0076] The surfaces of the field lenses can have various shapes. In an example implementation, the surfaces of the field lenses are described by the following equations:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{j=2}^{66} C_j x^m y^n$$

$$j = \frac{(m+n)^2 + m + 3n}{2} + 1$$

[0077] In some implementations, the first right field lens **530**R includes an outgoing surface **530**Ra and an incoming surface **530**Rb. The outgoing surface **530**Ra may be described with the following coefficients:

[0078] X2: −4.8329E-02
[0079] XY: 1.6751E-04
[0080] Y2: −4.4423E-02
[0081] X3: −2.6098E-04

[0082] The incoming surface **530**Rb may be described with the following coefficients:

[0083] X2: 5.8448E-02
[0084] XY: 5.3381E-03
[0085] Y2: 1.0536E-01
[0086] X3: −9.8277E-03

[0087] In some implementations, the second right field lens **532**R includes an outgoing surface **532**Ra and an incoming surface **532**Rb. The outgoing surface **532**Ra may be described with the following coefficients:

[0088] X2: −3.5719E-02
[0089] XY: −1.1015E-02
[0090] Y2: −3.5776E-02
[0091] X3: −1.3138E-04

[0092] The incoming surface **532**Rb may be described with the following coefficients:

[0093] X2: 9.1639E-03
[0094] XY: 1.2060E-02
[0095] XY2: 7.7082E-04

[0096] In some implementations, the third right field lens **534**R includes an outgoing surface **534**Ra and an incoming surface **534**Rb. The outgoing surface **534**Ra may be described with the following coefficients:

[0097] X2: −1.8156E-02
[0098] XY: 2.5627E-03
[0099] Y2: −1.1823E-02

[0100] The incoming surface **534**Rb may be described with the following coefficients:

[0101] X2: −6.9012E-03
[0102] XY: −2.1030E-02
[0103] Y2: −1.7461E-02

[0104] In some implementations, the fourth right field lens **536**R includes an outgoing surface **536**Ra and an incoming surface **536**Rb. The outgoing surface **536**Ra may be described with the following coefficients:

[0105] X2: −1.3611E-02
[0106] XY: −1.2595E-02
[0107] Y2: −2.4800E-02
[0108] X3: 7.8846E-05

[0109] The incoming surface **536**Rb may be described with the following coefficients:

[0110] X2: 1.9009E-02
[0111] XY: −3.3920E-03
[0112] Y2: 2.8645E-02

[0113] These equations and coefficients are just examples. Other implementations may include field lenses with surfaces defined by different equations and coefficients.

[0114] As noted above, the selection of field lenses formed from materials with different Abbe numbers may be used for color correction. Some implementations also include doublets in the field lenses to perform color correction. Additionally or alternatively, some implementations include a kinoform-type diffractive optical element in at least one of the field lenses. The equation and coefficients provided above are examples. Other implementations may use other equations and other coefficients.

[0115] FIG. **7** is a schematic diagram of a portion of an example HMD **700**. The HMD **700** is an example of the HMD **104**. In this example, the HMD **700** includes a frame **702**, right housing **704**R, a left housing **704**L, and a combiner **706**. The frame **702** may be similar to the frame **302**, the right housing **704**R and the left housing **704**L may be similar to the housing **304**, and the combiner **706** may be similar to the combiner **306**. In this example, the right housing **704**R and the left housing **704**L are both tilted at an angle relative to the horizontal direction of the user's face, as indicated at angle Φ. In some implementations, the angle Φ is 12 degrees. Other implementations use an angle between 5 and 15 degrees. Other implementations are also possible. This tilt may allow the overlay to clear a user's eyeglasses and therefore allow a user to wear the HMD **700** and glasses at the same time without the glasses occluding emitted visual content from reaching the combiner **706**. Some implementations are not configured to support a user wearing eyeglasses while wearing the HMD **700** and do not include this tilt relative to the horizontal direction of the user's face.

[0116] FIGS. **8**A and **8**B show schematic diagrams of another example implementation of an HMD **800** being worn over glasses by a user. FIG. **8**A shows an angled view from above of the HMD **800**. FIG. **8**B shows a front view of the HMD **800**. The HMD **800** is an example of the HMD **104**. In this example, the HMD **800** includes a combiner **806**, a right microdisplay device **808**R, a right prism **860**R, a right lens assembly **810**R, including right field lenses **830**R, **832**R, **834**R, and **836**R, and a right fold mirror assembly **812**R. The combiner **806** may be similar to the combiner **306**, the right microdisplay device **808**R may be similar to the microdisplay device **308**, the right lens assembly **810**R may be similar to the lens assembly **310**, and the right fold mirror assembly **812**R may be similar to the fold mirror assembly **312**. The right microdisplay device **808**R, the right prism **860**R, right lens assembly **810**R, and right fold mirror assembly **812**R are disposed in a right housing that is not shown in this figure. The right housing is disposed on the right side of the user's face and oriented so that content emitted by the microdisplay device **808**R is emitted through the right prism **860**R and the right lens assembly **810**R toward the right fold mirror assembly **812**R located in front of the user's face. The right fold mirror assembly **812**R then reflects the content to the combiner **806** that is disposed in front of the user's left eye.

[0117] In this example, the right field lenses **830**R and **832**R are joined to form a doublet. For example, the right field lenses **830**R and **832**R may be formed from materials having different Abbe numbers. The right prism **860**R may, for example, perform color correction and improve telecentricity. Embodiments that include a prism and doublets are illustrated and described elsewhere herein, such as with respect to at least FIG. **10**.

[0118] FIGS. **9**A-**9**D show schematic diagrams of another example implementation of an HMD **900** being worn by a user. FIG. **9**A shows an angled side view of the HMD **900**. FIG. **9**B shows a front view of the HMD **900**. FIG. **9**C shows a side view of the HMD **900**. FIG. **9**D shows a top view of the HMD **900**. The HMD **900** is an example of the HMD **104**. In this example, the HMD **900** includes a frame **902**, a right housing **904**R, a left housing **904**L, a combiner **906** that is connected to the frame **902** by an attachment assembly **970**, a right fold mirror assembly **912**R, and a left fold mirror assembly **912**L. The frame **902** may be similar to the frame **302**, the combiner **906** may be similar to the combiner **306**, the right fold mirror assembly **912**R and the left fold mirror assembly **912**L may be similar to the fold mirror assembly **312**. The right housing **904**R may enclose a right microdisplay device (not shown) and a right lens assembly **910**R. Similarly, the left housing **904**R may enclose a left microdisplay device (not shown) and a left lens assembly **910**L. The right lens assembly **910**R and the left lens assembly **910**L may be similar to the lens assembly **310**. In some implementations, the attachment assembly **970** includes one or more horizontally disposed elongate members that extend from the frame **902** out in front of the user's face. A first end of the attachment assembly **970** may be joined to the frame **902**, while a second end of the attachment assembly **970** may be joined to the combiner **906**. For example, the attachment assembly **970** may position the combiner **906** in front of the user's eyes so as to combine intermediary images generated by the right lens assembly **910**R and left lens assembly **910**L with the user's view of the physical environment (i.e., the real world).

[0119] FIG. **10** is a schematic diagram of a portion of an example HMD **1000**. The HMD **1000** is an example of the HMD **104**. In this example, the HMD **1000** includes a right microdisplay device **1008**R, a right lens assembly **1010**R, a combiner **1006**, and a right fold mirror assembly **1012**R. The right microdisplay device **1008**R may be similar to the microdisplay device **308**, the combiner **1006** may be similar to the combiner **306**, and the right fold mirror assembly **1012**R may be similar to the right fold mirror assembly **812**R. In this example, the right lens assembly **1010**R includes a right prism **1060**R, a doublet **1040**R, and a doublet **1042**R. The right prism **1060**R refracts light emitted by the right microdisplay device **1008**R. The right prism **1060**R may make the right lens assembly **1010**R more telecentric. The right prism **1060**R may, for example, improve the performance of the HMD **1000** when the right microdisplay device **1008**R includes LCOS technology.

[0120] The doublets **1040**R and **1042**R may reduce chromatic aberrations caused by the way the lenses affect light of different wavelengths differently. In some implementations, the doublet **1040**R includes a first lens **1050**R and a second lens **1052**R, and the doublet **1042**R includes a third lens **1054**R and a fourth lens **1056**R. The lenses may be formed from materials that have different Abbe numbers. For example, the first lens **1050**R and the third lens **1054**R may be formed from a first material that has an Abbe number equal to or approximately equal to 23.9 (e.g., a polycarbonate resin such as Lupizeta® EP-5000 from Mitsubishi Gas Chemical Company, Inc.) and the second lens **1052**R and the fourth lens **1056**R may be formed from a second material that has an Abbe number equal to or approximately equal to 56 (e.g., a cyclo olefin polymer material such as Zeonex® Z-E48R from Zeon Specialty Materials, Inc.).

[0121] FIG. **11** shows an example of a computing device **1100** and a mobile computing device **1150**, which may be used with the techniques described here. The computing device **1100** includes a processor **1102**, memory **1104**, a storage device **1106**, a high-speed interface **1108** connecting to memory **1104** and high-speed expansion ports **1110**, and a low speed interface **1112** connecting to low speed bus **1114** and storage device **1106**. Each of the components **1102**, **1104**, **1106**, **1108**, **1110**, and **1112**, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor **1102** can process instructions for execution within the computing device **1100**, including instructions stored in the memory **1104** or on the storage device **1106** to display graphical information for a GUI on an external input/output device, such as display **1116** coupled to high speed interface **1108**. In other implementations, multiple processors and/or multiple buses may be used, as appropriate, along with multiple memories and types of memory. Also, multiple computing devices **1100** may be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

[0122] The memory **1104** stores information within the computing device **1100**. In one implementation, the memory **1104** is a volatile memory unit or units. In another implementation, the memory **1104** is a non-volatile memory unit or units. The memory **1104** may also be another form of computer-readable medium, such as a magnetic or optical disk.

[0123] The storage device **1106** is capable of providing mass storage for the computing device **1100**. In one implementation, the storage device **1106** may be or contain a computer-readable medium, such as a floppy disk device, a hard disk device, an optical disk device, or a tape device, a flash memory or other similar solid state memory device, or an array of devices, including devices in a storage area network or other configurations. A computer program product can be tangibly embodied in an information carrier. The computer program product may also contain instructions that, when executed, perform one or more methods, such as those described above. The information carrier is a computer- or machine-readable medium, such as the memory **1104**, the storage device **1106**, or memory on processor **1102**.

[0124] The high speed controller **1108** manages bandwidth-intensive operations for the computing device **1100**, while the low speed controller **1112** manages lower bandwidth-intensive operations. Such allocation of functions is exemplary only. In one implementation, the high-speed controller **1108** is coupled to memory **1104**, display **1116** (e.g., through a graphics processor or accelerator), and to high-speed expansion ports **1110**, which may accept various expansion cards (not shown). In the implementation, low-speed controller **1112** is coupled to storage device **1106** and low-speed expansion port **1114**. The low-speed expansion port, which may include various communication ports (e.g., USB, Bluetooth, Ethernet, wireless Ethernet) may be coupled to one or more input/output devices, such as a keyboard, a pointing device, a scanner, or a networking device such as a switch or router, e.g., through a network adapter.

[0125] The computing device **1100** may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a standard server **1120**, or multiple times in a group of such servers. It may also be implemented as part of a rack server system **1124**. In addition, it may be implemented in a personal computer such as a laptop computer **1122**. Alternatively, components from computing device **1100** may be combined with other components in a mobile device (not shown), such as device **1150**. Each of such devices may contain one or more of computing device **1100**, **1150**, and an entire system may be made up of multiple computing devices **1100**, **1150** communicating with each other.

[0126] Computing device **1120** includes a processor **1152**, memory **1164**, an input/output device such as a display **1154**, a communication interface **1166**, and a transceiver **1168**, among other components. The device **1150** may also be provided with a storage device, such as a microdrive or other device, to provide additional storage. Each of the components **1150**, **1152**, **1164**, **1154**, **1166**, and **1168**, are interconnected using various buses, and several of the components may be mounted on a common motherboard or in other manners as appropriate.

[0127] The processor **1152** can execute instructions within the computing device **1120**, including instructions stored in the memory **1164**. The processor may be implemented as a chipset of chips that include separate and multiple analog and digital processors. The processor may provide, for example, for coordination of the other components of the device **1150**, such as control of user interfaces, applications run by device **1150**, and wireless communication by device **1150**.

[0128] Processor **1152** may communicate with a user through control interface **1158** and display interface **1156** coupled to a display **1154**. The display **1154** may be, for example, a TFT LCD (Thin-Film-Transistor Liquid Crystal Display) or an OLED (Organic Light Emitting Diode) display, or other appropriate display technology. The display interface **1156** may comprise appropriate circuitry for driving the display **1154** to present graphical and other information to a user. The control interface **1158** may receive commands from a user and convert them for submission to the processor **1152**. In addition, an external interface **1162** may be provide in communication with processor **1152**, so as to enable near area communication of device **1150** with other devices. External interface **1162** may provide, for example, for wired communication in some implementations, or for wireless communication in other implementations, and multiple interfaces may also be used.

[0129] The memory **1164** stores information within the computing device **1120**. The memory **1164** can be implemented as one or more of a computer-readable medium or media, a volatile memory unit or units, or a non-volatile memory unit or units. Expansion memory **1174** may also be provided and connected to device **1150** through expansion interface **1172**, which may include, for example, a SIMM (Single In Line Memory Module) card interface. Such expansion memory **1174** may provide extra storage space for device **1150**, or may also store applications or other information for device **1150**. Specifically, expansion memory **1174** may include instructions to carry out or supplement the processes described above, and may include secure information also. Thus, for example, expansion memory **1174** may be provided as a security module for device **1150**, and may be programmed with instructions that permit secure use of device **1150**. In addition, secure applications may be provided via the SIMM cards, along with additional information, such as placing identifying information on the SIMM card in a non-hackable manner.

[0130] The memory may include, for example, flash memory and/or NVRAM memory, as discussed below. In one implementation, a computer program product is tangibly embodied in an information carrier. The computer program product contains instructions that, when executed, perform one or more methods, such as those described above. The information carrier is a computer- or machine-readable medium, such as the memory **1164**, expansion memory **1174**, or memory on processor **1152**, that may be received, for example, over transceiver **1168** or external interface **1162**.

[0131] Device **1150** may communicate wirelessly through communication interface **1166**, which may include digital signal processing circuitry where necessary. Communication interface **1166** may provide for communications under various modes or protocols, such as GSM voice calls, SMS, EMS, or MMS messaging, CDMA, TDMA, PDC, WCDMA, CDMA2000, or GPRS, among others. Such communication may occur, for example, through radio-frequency transceiver **1168**. In addition, short-range communication may occur, such as using a Bluetooth, Wi-Fi, or other such transceiver (not shown). In addition, GPS (Global Positioning System) receiver module **1170** may provide additional navigation- and location-related wireless data to device **1150**, which may be used as appropriate by applications running on device **1150**.

[0132] Device **1150** may also communicate audibly using audio codec **1160**, which may receive spoken information from a user and convert it to usable digital information. Audio codec **1160** may likewise generate audible sound for a user, such as through a speaker, e.g., in a handset of device **1150**. Such sound may include sound from voice telephone calls, may include recorded sound (e.g., voice messages, music files, etc.) and may also include sound generated by applications operating on device **1150**.

[0133] The computing device **1120** may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a cellular telephone **1180**. It may also be implemented as part of a smart phone **1182**, personal digital assistant, or other similar mobile device.

[0134] Various implementations of the systems and techniques described here can be realized in digital electronic circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

[0135] These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the terms “machine-readable medium” “computer-readable medium” refers to any computer program product, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term “machine-readable signal” refers to any signal used to provide machine instructions and/or data to a programmable processor.

[0136] To provide for interaction with a user, the systems and techniques described here can be implemented on a computer having a display device (e.g., an LCD (liquid crystal display) screen, an OLED (organic light emitting diode)) for displaying information to the user and a keyboard and a pointing device (e.g., a mouse or a trackball) by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback); and input from the user can be received in any form, including acoustic, speech, or tactile input.

[0137] The systems and techniques described here can be implemented in a computing system that includes a back end component (e.g., as a data server), or that includes a middleware component (e.g., an application server), or that includes a front end component (e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation of the systems and techniques described here), or any combination of such back end, middleware, or front end components. The components of the system can be interconnected by any form or medium of digital data communication (e.g., a communication network). Examples of communication networks include a local area network (“LAN”), a wide area network (“WAN”), and the Internet.

[0138] The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

[0139] In some implementations, the computing devices depicted in FIG. **1** can include sensors that interface with an AR headset/HMD device **1190** to generate an AR environment. For example, one or more sensors included on a computing device **1120** or other computing device depicted in FIG. **1**, can provide input to AR headset **1190** or in general, provide input to a AR environment. The sensors can include, but are not limited to, a touchscreen, accelerometers, gyroscopes, pressure sensors, biometric sensors, temperature sensors, humidity sensors, and ambient light sensors. The computing device **1120** can use the sensors to determine an absolute position and/or a detected rotation of the computing device in the AR environment that can then be used as input to the AR environment. For example, the computing device **1120** may be incorporated into the AR space as a virtual object, such as a controller, a laser pointer, a keyboard, a weapon, etc. Positioning of the computing device/virtual object by the user when incorporated into the

AR environment can allow the user to position the computing device so as to view the virtual object in certain manners in the AR environment. For example, if the virtual object represents a laser pointer, the user can manipulate the computing device as if it were an actual laser pointer. The user can move the computing device left and right, up and down, in a circle, etc., and use the device in a similar fashion to using a laser pointer.

[0140] In some implementations, one or more input devices included on, or connect to, the computing device **1120** can be used as input to the AR environment. The input devices can include, but are not limited to, a touchscreen, a keyboard, one or more buttons, a trackpad, a touchpad, a pointing device, a mouse, a trackball, a joystick, a camera, a microphone, earphones or buds with input functionality, a gaming controller, or other connectable input device. A user interacting with an input device included on the computing device **1120** when the computing device is incorporated into the AR environment can cause a particular action to occur in the AR environment.

[0141] In some implementations, a touchscreen of the computing device **1120** can be rendered as a touchpad in AR environment. A user can interact with the touchscreen of the computing device **1120**. The interactions are rendered, in AR headset **1190** for example, as movements on the rendered touchpad in the AR environment. The rendered movements can control virtual objects in the AR environment.

[0142] In some implementations, one or more output devices included on the computing device **1120** can provide output and/or feedback to a user of the AR headset **1190** in the AR environment. The output and feedback can be visual, tactical, or audio. The output and/or feedback can include, but is not limited to, vibrations, turning on and off or blinking and/or flashing of one or more lights or strobes, sounding an alarm, playing a chime, playing a song, and playing of an audio file. The output devices can include, but are not limited to, vibration motors, vibration coils, piezoelectric devices, electrostatic devices, light emitting diodes (LEDs), strobes, and speakers.

[0143] In some implementations, the computing device **1120** may appear as another object in a computer-generated, 3D environment. Interactions by the user with the computing device **1120** (e.g., rotating, shaking, touching a touchscreen, swiping a finger across a touch screen) can be interpreted as interactions with the object in the AR environment. In the example of the laser pointer in an AR environment, the computing device **1120** appears as a virtual laser pointer in the computer-generated, 3D environment. As the user manipulates the computing device **1120**, the user in the AR environment sees movement of the laser pointer. The user receives feedback from interactions with the computing device **1120** in the AR environment on the computing device **1120** or on the AR headset **1190**.

[0144] In some implementations, a computing device **1120** may include a touchscreen. For example, a user can interact with the touchscreen in a particular manner that can mimic what happens on the touchscreen with what happens in the AR environment. For example, a user may use a pinching-type motion to zoom content displayed on the touchscreen. This pinching-type motion on the touchscreen can cause information provided in the AR environment to be zoomed. In another example, the computing device may be rendered as a virtual book in a computer-generated, 3D environment. In the AR environment, the pages of the book can be displayed in the AR environment and the swiping of a finger of the user across the touchscreen can be interpreted as turning/flipping a page of the virtual book. As each page is turned/flipped, in addition to seeing the page contents change, the user may be provided with audio feedback, such as the sound of the turning of a page in a book.

[0145] In some implementations, one or more input devices in addition to the computing device (e.g., a mouse, a keyboard) can be rendered in a computer-generated, 3D environment. The rendered input devices (e.g., the rendered mouse, the rendered keyboard) can be used as rendered in the AR environment to control objects in the AR environment.

[0146] Computing device **1100** is intended to represent various forms of digital computers and devices, including, but not limited to laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. Computing device **1120** is intended to represent various forms of mobile devices, such as personal digital assistants, cellular telephones, smart phones, and other similar computing devices. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit implementations of the inventions described in this document.

[0147] A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the specification.

[0148] In addition, the logic flows depicted in the figures do not require the particular order shown, or sequential order, to achieve desirable results. In addition, other steps may be provided, or steps may be eliminated, from the described flows, and other components may be added to, or removed from, the described systems. Accordingly, other embodiments are within the scope of this disclosure.

[0149] While certain features of the described implementations have been illustrated as described herein, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It should be understood that they have been presented by way of example only, not limitation, and various changes in form and details may be made. Any portion of the apparatus and/or methods described herein may be combined in any combination, except mutually exclusive combinations. The implementations described herein can include various combinations and/or sub-combinations of the functions, components and/or features of the different implementations described.

What is claimed is:

1. A head-mounted display device, comprising:

a frame having a structure that is configured to be worn by a user;

a combiner that is attached to the frame and includes a curved transparent structure having a reflective surface; and

a microdisplay device attached to the frame and configured to, when the frame is worn by the user, emit image content that crosses in front of the user's face and intersects with the reflective surface of the combiner.

2. The head-mounted display device of claim **1**, wherein, when the frame is worn, the microdisplay device is configured to emit image content that crosses a sagittal plane of the user's face before intersecting with the reflective surface of the combiner.

3. The head-mounted display device of claim 1, further comprising a lens assembly disposed along an optical axis between the microdisplay device and the combiner.

4. The head-mounted display device of claim 3, wherein the lens assembly includes a plurality of field lenses oriented along the optical axis.

5. The head-mounted display device of claim 4, wherein the lens assembly further includes a doublet configured to perform color correction.

6. The head-mounted display device of claim 4, wherein at least one field lens of the plurality of field lenses includes a kinoform-type diffractive optical element.

7. The head-mounted display device of claim 1, wherein the combiner has a positive wrap angle.

8. The head-mounted display device of claim 7, wherein the combiner includes an outer surface that is opposite the reflective surface and has a convex curvature.

9. The head-mounted display device of claim 1, wherein the frame includes a left arm configured to rest on the user's left ear and a right arm configured to rest on the user's right ear.

10. The head-mounted display device of claim 9, further comprising a housing mounted to the left arm of the frame, the housing including the microdisplay device and the microdisplay device being configured to emit image content for the user's right eye.

11. The head-mounted display device of claim 10, further comprising a fold mirror attached to the frame and configured to reflect image content emitted by the microdisplay device toward the combiner.

12. An augmented reality head-mounted display device, comprising:

a frame having a structure that is configured to be worn by a user;

a combiner that is attached to the frame and has an inner surface and an outer surface, the inner surface being reflective and the outer surface having a positive wrap angle; and

a microdisplay device attached to the frame and configured to, when the frame is worn by the user, emit image content that intersects with the inner surface of the combiner.

13. The augmented reality head-mounted display device of claim 12, wherein, when the frame is worn, the outer surface of the combiner faces away from the user and has a convex curvature.

14. The augmented reality head-mounted display device of claim 13, wherein the curvature of the outer surface of the combiner is smooth.

15. The augmented reality head-mounted display device of claim 14, wherein the curvature of the outer surface being smooth includes the curvature of the outer surface having a continuous first derivative.

16. The augmented reality head-mounted display device of claim 12, wherein, when the frame is worn by the user, the microdisplay device is configured to emit image content that crosses in front of the user's face and intersects with the inner surface of the combiner.

17. The head-mounted display device of claim 16, wherein, when the frame is worn, the microdisplay device is configured to emit image content that crosses a sagittal plane of the user's face before intersecting with the inner surface of the combiner.

18. A head-mounted display device, comprising:

a frame having a structure that is configured to be worn by a user, the frame including a left arm configured to rest on the user's left ear and a right arm configured to rest on the user's right ear;

a combiner that is attached to the frame and includes a curved transparent structure that has an inner surface and an outer surface, the inner surface being reflective;

a left microdisplay device attached to the frame and configured to emit image content for the user's right eye, the left microdisplay device emitting image content so that the image content crosses in front of the user's face and intersects with the inner surface of the combiner; and

a right microdisplay device attached to the frame and configured to emit image content for the user's left eye, the right microdisplay device emitting image content so that the image content crosses in front of the user's face and intersects with the inner surface of the combiner.

19. The head-mounted display device of claim 18, wherein the combiner has a positive wrap angle.

20. The head-mounted display device of claim 18, wherein the combiner is attached to the frame via an attachment assembly that, when worn by the user, extends out in front of the user's face.

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